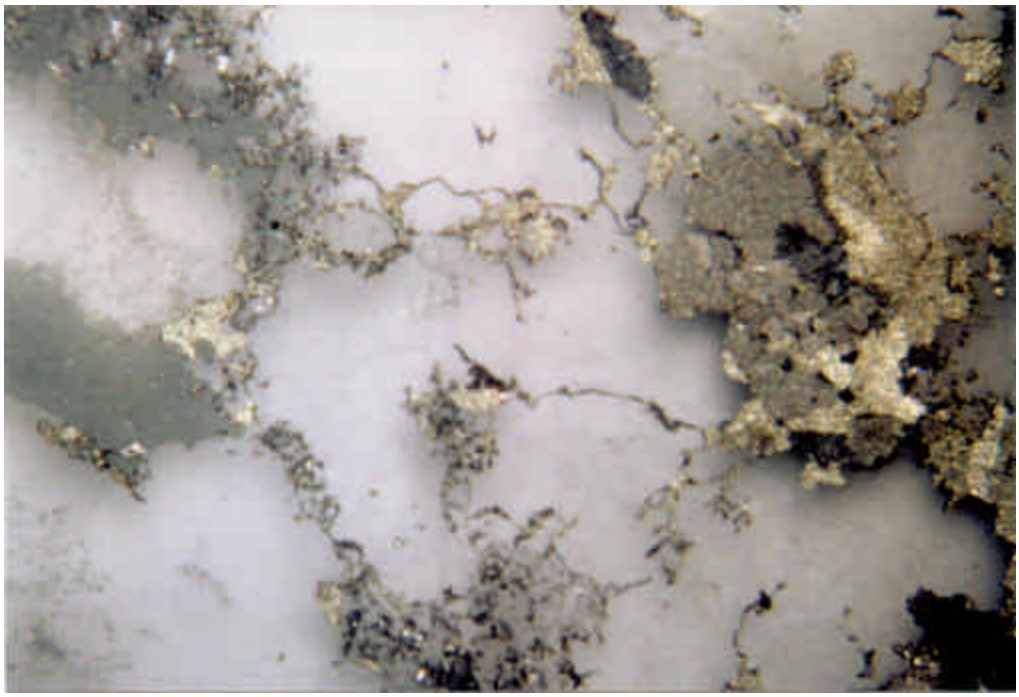
LES MINES SELBAIE



DECOMMISSIONING

WITH ECOLOGICAL ENGINEERING

November 1992

(Cover photo: Thin section of pyrite used in the Waste Rock Experiment)

EXECUTIVE SUMMARY

Cost associated with conventional decommissioning options for Les Mines Selbaie range from $10 to $50 million for the tailings, and $5 to $15 million for the waste rock pile. Les Mines Selbaie has engaged the services of Boojum Research Ltd. since 1990, to identify a less costly decommissioning scenario. Ideally, this scenario would not include the operation of a conventional treatment plant for perpetuity.

In 1990 and 1991, an Ecological Engineering decommissioning concept was outlined for the tailings and waste rock management areas, based on an assessment of a thorough water quality monitoring program.

During development of the concept, the exceptionally high acidities and metal concentrations, particularly iron, characteristic of Selbaie waste rock and tailings seepages, could not be overlooked. Neutralization and removal of metals from Selbaie's acid mine drainage (AMD) would require approximately 5.7 million tonnes of lime over 285 years, and generate 30 million m^3 of sludge.

In 1992, the focus of field and lab investigations was the testing of natural phosphate rock (NPR), as part of a low-maintenance passive system for treatment of AMD. NPR has the capacity to reduce acidity and precipitate iron, producing a higher density sludge than that resulting from lime treatment. Once the bulk of the iron content is removed from AMD, both algal and microbial (ARUM) populations can be utilized to remove remaining metals and complete neutralization.

A field test system was constructed on-site in July, and intermittently operated during three runs until freeze-up in October, 1992. In the test system, B-Ditch AMD was delivered by pumps from a feed tank to three tanks containing NPR. NPR-treated water passed through a settling tank before discharge into two Biological Polishing pools in series, inoculated with algae indigenous to AMD. A tank containing substrates for initiating an alkalinity-generating bacterial population (ARUM) was set-up, but was not part of the flow path during operation of the test system during 1992.

During operation of the field test system, NPR significantly improved the quality of AMD. The average reduction in iron concentrations was 60%, while the average reduction in acidity was 35%. The reactivity of NPR was demonstrated to last for at least 47 days (over Runs 2 and 3) without replacement.

Accumulation of precipitates among NPR granules resulted in reduced permeability, or plugging, of the NPR treatment component in as few as 14 days of operation. However, it should be possible to extend the operating period before plugging by modifying the placement configuration of NPR, including reduction of the NPR layer thickness, combined with periodic agitation.

Adequately large algal populations, the primary component of the Biological Polishing, did not establish before freeze-up, and suspended metal removal could not be demonstrated during the 1992 trials.

At the time the ARUM component was set up, NPR pre-treated water was not available, and this tank was filled with raw AMD. As this delayed the onset of ARUM microbial community, the ARUM component was not brought on line during 1992 trials.

During 1992, laboratory ARUM experiments demonstrated complete microbially-mediated metal removal and acid neutralization of B-Ditch AMD. Demonstration of the ARUM component, as well as Biological Polishing, in the field test system is anticipated by summer 1993, when algal and bacterial populations have had time to reach sufficient density.

A laboratory bench scale experiment was designed for examining, in detail, the reactions between AMD and NPR at the same ratio of flow to NPR volume as the field test. Each week, over a 51 day period, the system was dismantled, the precipitate recovered and the system reassembled, permitting close tracking the performance of the single batch of NPR over time.

The average dissolved iron removal was greater than 99% over the entire period of operation, while acidity reduction averaged 67%. Although pH increases following NPR treatment were only slight during the last week of operation, virtually all iron was still being removed, and acidity was still reduced by 48%. Operation ceased when the feed AMD supply was depleted (160 L).

Two distinct types of precipitate were formed during operation. Orange precipitates, formed upon passage of AMD through the NPR granules, were primarily composed of iron and aluminum hydroxides, as well as gypsum. Light green precipitate, formed in the settling tanks (equivalent to the Biological Polishing tanks) following NPR treatment, were composed of 25% copper, 8% zinc, but very little iron and phosphate (~1%). The combined total sludge volume was 62% less than that expected by using lime to neutralize the AMD to pH 6.

The excellent iron removal performance by NPR in the bench-scale experiments was due to formation of ferric phosphate and hydroxide precipitation, following near complete oxidation of ferrous iron to ferric iron during storage of the AMD stock solution. Zinc and copper precipitates were likely carbonates, formed by diffusion of carbon dioxide into the NPR-treated, alkalinity-bearing water. These are expected to be removed by biological polishing.

During 1992, two experiments addressing the prevention of acid generation by waste rock and tailings have been initiated. The waste rock experiment, constructed outdoors, is examining the effectiveness of both spent and new NPR in terms of curtailing acid generation, through the formation of secondary mineralization over waste rock surfaces.

Within the first 22 days following set-up, acid generation in the waste rock drums was evident in the control drums. The results also suggest that NPR added to some treatments may already be retarding the acid generation process. The monitoring program will periodically record both the overall effluent water chemistry, and microscopic composition of waste rock surface mineralization, for the next two years.

The tailings column experiment designed in 1992 is based on the premise that, if water penetration into tailings is reduced, and its oxygen content eliminated, generation of acid by tailings can be curtailed. A continuous layer of NPR, overlain with a vegetation layer, should result in development of a low permeability stratum (iron precipitate hardpan) beneath the vegetation layer, and provide suitable conditions for heterotrophic (oxygen- consuming) bacteria in the root zone.

Successful techniques for establishing vegetation covers over fresh tailings were developed during field trials in 1990 and 1991. Vegetation plots have twice overwintered, and heterotrophic bacterial populations are present. Determination of the optimal configuration and effectiveness of such a cover demands a high level of control over many parameters, practically achievable only in the laboratory.

The design of the tailings column experiment has to include, for example, both control and detailed measurement of water content in the saturated, capillary and dry zones of the tailings columns. Time domain reflectometry has been identified as the most appropriate monitoring tool. Given the costs associated with measurement of these and other parameters, an application has been made for funding from NRC.

In 1992, Boojum Research Ltd. demonstrated the utility of NPR for AMD treatment through removal of iron and reduction of acidity. In addition, Boojum has initiated two further investigations examining acid generation prevention using NPR alone, or in combination with plant and bacterial populations. Overall, significant advances have been made towards completing the technical foundation required for a low-maintenance Ecological Engineering close-out strategy for Les Mines Selbaie.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SCHEMATICS

LIST OF MAPS

LIST OF PLATES

1. INTRODUCTION

In January l990, Golder Associates submitted a report entitled "Waste Management Review, Selbaie Mine, Quebec". Chapters 8 and 9 addressed decommissioning options and plans for the site. Costs associated with the conventional options ranged from $10 to $50 million for the tailings, and $5 to $15 million for the waste rock pile.

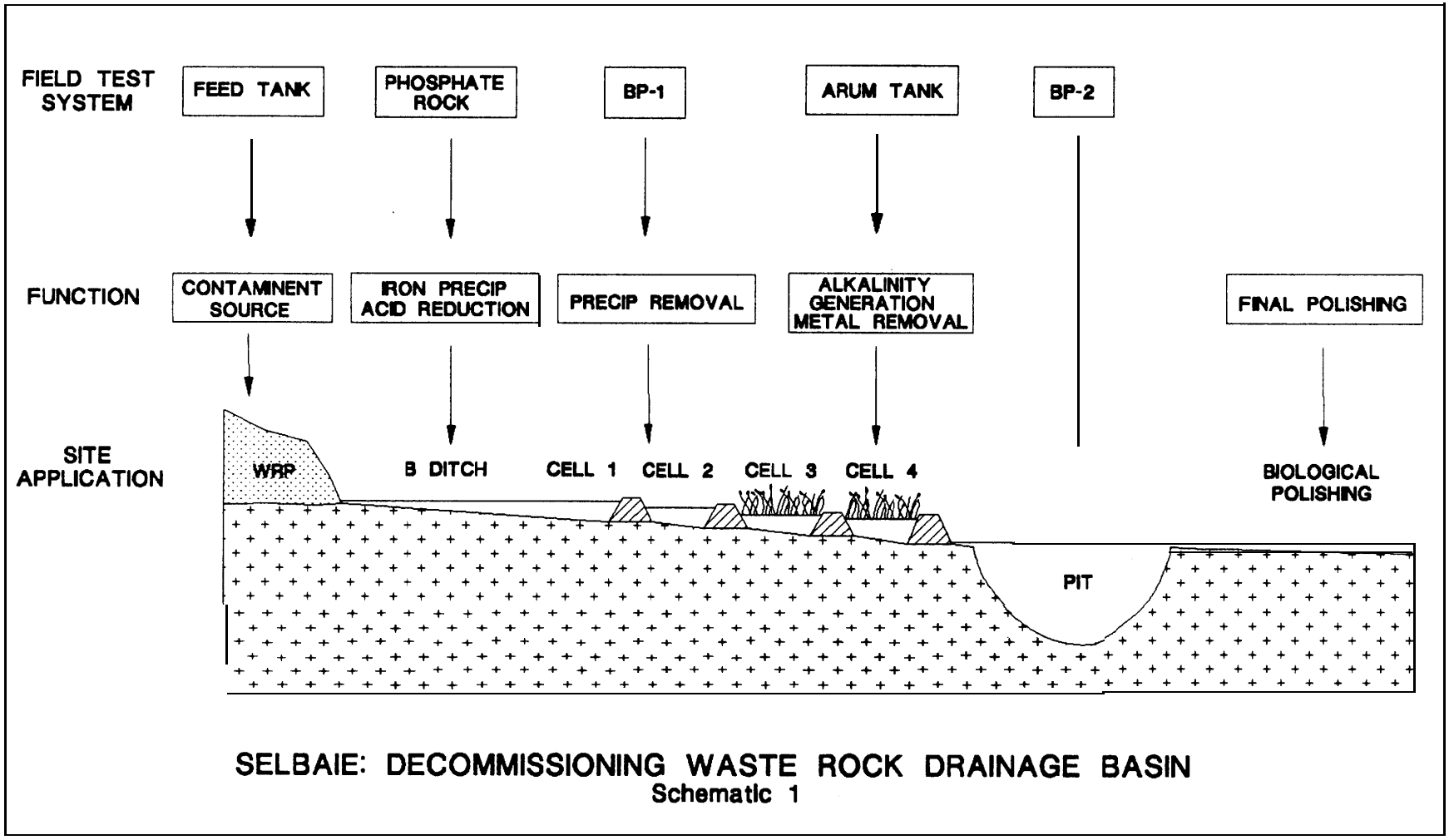
In light of these costs, and the reality of perpetual treatment, Les Mine Selbaie engaged the services of Boojum Research Ltd. in l990 and l991, in order to determine whether there might be other decommissioning options meriting consideration.

Between 1990 and 1991, an Ecological Engineering decommissioning concept was developed for Les Mines Selbaie, addressing three aspects:

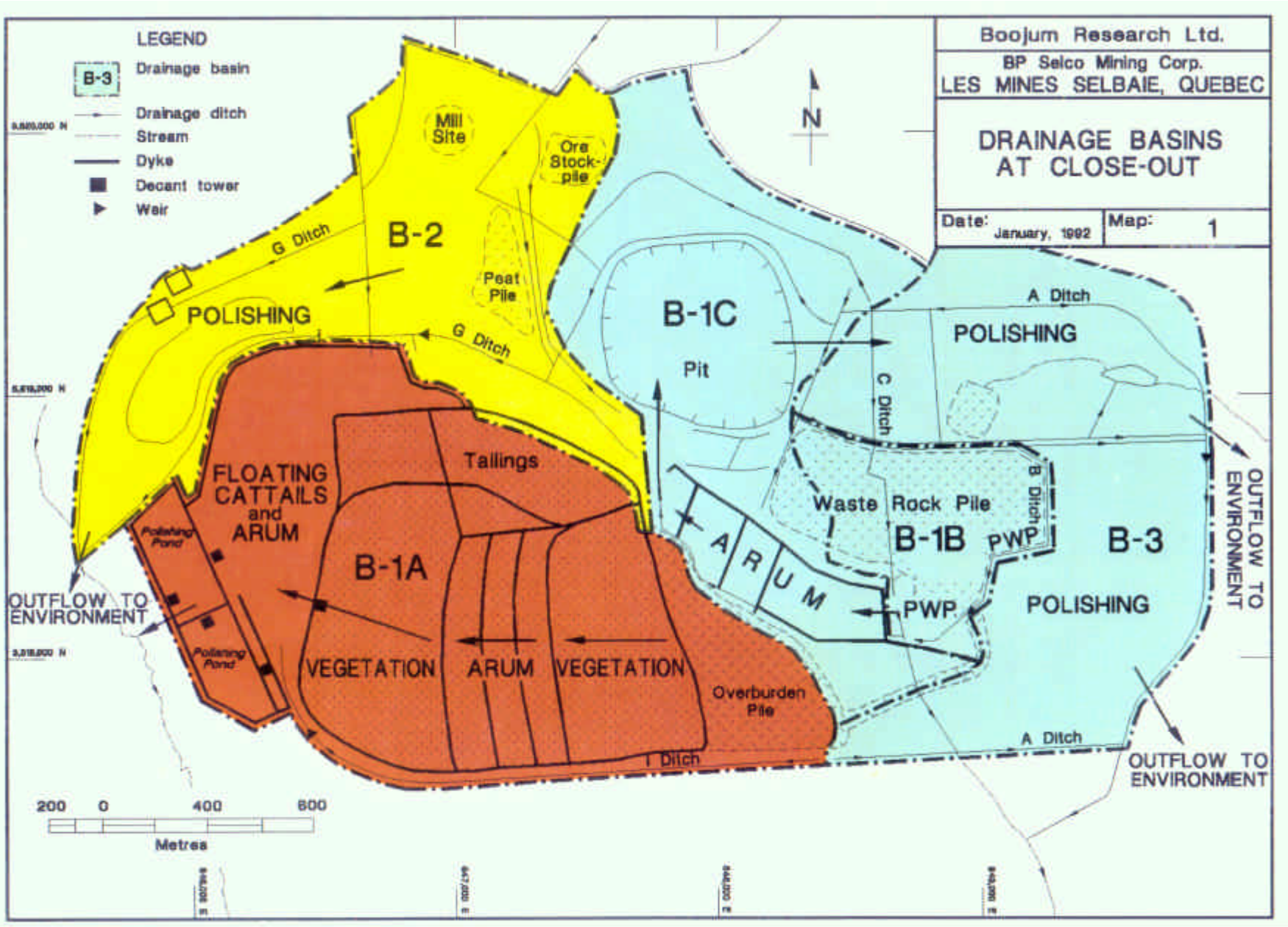
1) the tailings area,
2) the waste rock pile and its seepage, and
3) preventive measures for AMD generation, for both waste rock and tailings.

In Schematic 1, the overall concept, developed in l991, is given, including those steps required to arrive at a low-maintenance decommissioning scenario. The lower part of the figure depicts the waste rock pile, where seepages emerge and drain into B-Ditch, located upstream from the cells comprising the collection pond. It is envisaged that, at the time of decommissioning, flow will be diverted into the pit. When filled, the pit will overflow, whereupon drainage will leave the waste management area via Area C (Map 1), then to the perimeter ditch and finally to the environment.

ARUM-treated water entering the pit will mix with ground water, which is assumed to be uncontaminated. Areas C and B-3 could be utilized if further polishing is required (Map 1).



SELBAIE: DECOMMISSIONING WASTE ROCK DRAINAGE BASIN
Schematic 1


LEGEND
B-3
Drainage basin
Drainage ditch
Stream
Dyke
Decant tower
Weir
Boojum Research Ltd.
BP Selco Mining Corp.
LES MINES SELBAIE, QUEBEC
DRAINAGE BASINS AT CLOSE-OUT
Date: January, 1992
Map: 1
N
Mill Site
Ore Stock-pile
Peat Pile
B-2
G Ditch
POLISHING
G Ditch
B-1C
Pit
A Ditch
POLISHING
C Ditch
FLOATING CATTAILS and ARUM
Tailings
B-1A
Waste Rock Pile
B-1B
PWP
B Ditch
B-3
ARUM
PWP
POLISHING
OUTFLOW TO ENVIRONMENT
Polishing Pond
Polishing Pond
OUTFLOW TO ENVIRONMENT
VEGETATION
ARUM
VEGETATION
Overburden Pile
I Ditch
A Ditch
OUTFLOW TO ENVIRONMENT
200 0 400 600
Metres

The middle section of Schematic 1 outlines each functional component of the decommissioning concept. Natural phosphate rock precipitates iron and reduces acidity, thereby pre-treating B-Ditch water. Pre-treated water then passes through an algal polishing step in Cells 1 and 2, where the suspended (mobile) fraction of precipitates, formed by NPR pre-treatment, are relegated to the sediment. Water then passes through Cell 3 and Cell 4, where dissolved metal concentrations are reduced, and alkalinity increased, by the microbial process, ARUM. Floating cattail mats cover Cells 3 and 4 to minimize water oxygenation, thereby maintaining reducing conditions.

Field test system components, listed across the uppermost portion of Schematic 1, are depicted directly above their counterparts in the proposed decommissioning concept described above.

In 1992, the work focused primarily on the second aspect, the waste rock pile drainage basin.

The acidity and the metal content of this water is such, that algal and microbial populations, although present, are not able to improve the seepage. In July 1990, hay bales were placed in B-Ditch, as a food supply for acid-reducing microbial ecosystems (ARUM). Their placement was based on an assessment of water quality prior to completion of B-Ditch construction. At that time, dilute AMD was prevalent, while the pH of Hockey Lake was still neutral. However, over the remainder of 1990, the acidity and iron content of B-Ditch water more than tripled, and the hay bales have become heavily coated with iron hydroxide precipitate, rendering them ineffective.

During l991, Boojum, together with Selbaie personnel, established permanent sampling locations in the waste management area. Water monitoring stations were established to facilitate an assessment of AMD trends (Map 1). An evaluation of the data available at the end l991 (summarized in a database) indicated that a pre-treatment step was required. After comparing Selbaie seepage chemistry with that reported for other AMD sites, it became

evident that seepage characteristics (as of late l991) were not necessarily those which would prevail in the long term. Research towards improving B-Ditch water was therefore considered prudent, not only for development of a low-maintenance decommissioning concept, but also to identify methods to reduce total sludge volume production.

Sludge is presently disposed of in the tailings pond. One drawback of this disposal practice is that it likely contributes to problems with the final effluent. It also represents a liability at the time of decommissioning, in that metal-rich sludges are deposited with acid-generating tailings. Furthermore, the sludge consumes tailings pond volume, thereby shortening the operating life of the tailings pond.

Natural phosphate rock (NPR) might be used to precipitate iron and reduce the acidity in the seepage. It could be used in B-Ditch to remove the ferric iron from seepages, and then be disposed of in the waste rock.

Further, if secondary minerals can be formed on the surface of the rocks, then acid generation might cease. Evidence for this proposition comes from the Gibraltar waste rock pile, which was used as a heap leach system. It ceased to function and no longer produced either metals or acid. When the pile was investigated, it was noted that the rock was covered with secondary minerals. NPR may provide the means to "coat" waste rock with secondary minerals.

The work in l992 was centred on testing the performance of NPR and demonstrating, on-site, the key processes which would be part of the decommissioning scenario. These processes are:

- precipitation of iron with NPR.
- growth of algae in NPR-treated water.
- ARUM (Acid Reduction Using Microbiology) initiation.

To test performance of NPR, three major experimental systems were set up in 1992. The first was a multi-stage, flow-through experimental system which was built on site in July, and operated between July and October, 1992. This system would test NPR as a pre-treatment for AMD from waste rock piles. This work is described in Sections 2,3,4 of the report.

The construction of the field test system experienced some delays, in part due to the delayed arrival of NPR. Some operational problems were also encountered, including the absence of an indigenous algal biomass supply, due to deterioration of the B-Ditch water quality since l991.

Algae imported from one AMD site did not survive. However, successful colonization by algae imported from a second site was achieved. Overall, this resulted in a very short growth period for second batch of algal biomass in the system; no field data concerning the growth or uptake by this biomass was collected for evaluation of BP-1 and BP-2 performance.

While the field system was operating, laboratory work at Boojum examined NPR chemistry, algal growth in NPR-treated B-Ditch water, and ARUM onset in experiments set up in 1990. The results of these laboratory experiments, as well as observations of the onset of microbial activity in the field system ARUM tank, were all very promising. Full operation can be expected in 1993, now that construction and operational "bugs" have been worked out.

The second experiment addressed the design and set-up of a waste rock /NPR testing facility at Boojum. Waste rock of different mineralogies and stages of weathering was collected at Selbiae to test the performance of spent NPR and fresh NPR to facilitate the formation of secondary minerals on waste rock. Rocks from the Gibraltar heap leach have been obtained by Boojum, and will serve as a comparison, when secondary mineral formation in the waste rock experiment is being evaluated.

In light of the decommissioning problems with waste rock piles and the present state of technology, the most important research should address means to curtail AMD. The heap leach of Gibraltar mines has ceased to function through the generation of secondary minerals on the rock surface. As spent NPR will contain precipitates, disposing of these into the waste rock pile, as they are no longer reactive, might provide the needed coating on the rock surface. The waste rock experiments are discussed in Section 5.

For tailings, preventive covers might consist of a combination of vegetation with oxygen-consuming bacteria along with formation of a hardpan with NPR in the vadose zone of the tailings mass. If NPR is layered onto fresh tailings, in conjunction with vegetation, movement of water and oxygen into the tailings might be reduced or eliminated. In 1990/1991 Selbaie supported the first sets of experiments, which proved that: 1) vegetation can be established on fresh tailings; 2) vegetation will overwinter; and 3) heterotrophs are indigenous to the root zone. This work was successful and therefore the third objective of the l992 work was to design a tailings column experiment which would facilitate measurements of the effectiveness of such a cover. The tailings column designs are discussed in Section 6.

2. THE FIELD TEST SYSTEM

Plate 1 shows the on-site test system. The general flow sheet for the system is shown in Schematic 2. Construction details are provided in a longitudinal section in the Appendix. The first part of the system is designed to remove iron, through precipitation with NPR. Water stored in the feed tank passes through phosphate rock (PR-1, PR-2 and PR-3) and drains into the settling tank. The second part of the system is designed for biological cleansing of water, as it passes through Biological Polishing pools BP-1, the ARUM tank, and BP-2.

PLATE 1: Overview of the field test system. The ARUM tank is in the foreground. The blue barrels are the phosphate rock containers, PR-1, PR-2 and PR-3. The feed tank and distributor system are in the background.

Les Mines Selbaie
FLOWSHEET OF ON-SITE TEST SYSTEM
Schematic 2

As with any process, the flow path and treatment sequence are very important. After dissolved iron concentrations and acidity in the AMD feed have been reduced by percolation through NPR, the first Biological Polishing pool (BP-1), containing algae, removes any remaining suspended precipitates. Water then enters the ARUM tank, where the pH is raised further through microbial action, and the dissolved metals are precipitated from solution. ARUM overflow enters a second Biological Polishing step (BP-2), for removal of any remaining precipitates and metals.

The establishment of the system's biological components (algal and microbial populations) is not instantaneous. As with all living things, weeks must pass before biological systems are of sufficient size to be operational. A significant metal removal capacity can be expected only after a full growing season, while full capacity can be anticipated only after several growing seasons.

Due to the delayed arrival of NPR on site, the ARUM tank was not filled with NPR pre-treated water, but with virtually raw AMD. An attempt was made to substitute the NPR treatment with a bone meal treatment, but this was not successful, in terms of reduced iron concentration and acidity. The minimum pH at which ARUM communities will rapidly develop is around 3.5. However, without the NPR pre-treatment, acidity remained high at 4,000 mg/L $CaCO_3$, and the pH was only 2.5. As the onset of ARUM was in fact delayed by the low pH, it was decided that flow through the system would be diverted around ARUM, and that when ARUM was fully established, it would be brought on-line. It is expected that this will occur in l993.

The pH values for the field system are summarized in Figure 1a (Feed tank, PR-1 to PR-3 and Settling Tank) and Figure 1b (Settling Tank, BP-1 and BP-2). The data are separated into Run 1, the first period between start-up and NPR plugging after 17 days; Run 2, the next period, used new NPR, and lasted for 13 days until plugging; and Run 3, the next period after the NPR had been washed, lasted until winter freeze-up.

Fig. 1a: Selbaie - Field Test System
Feed Tank, PR1,2,3 and Settling Tank

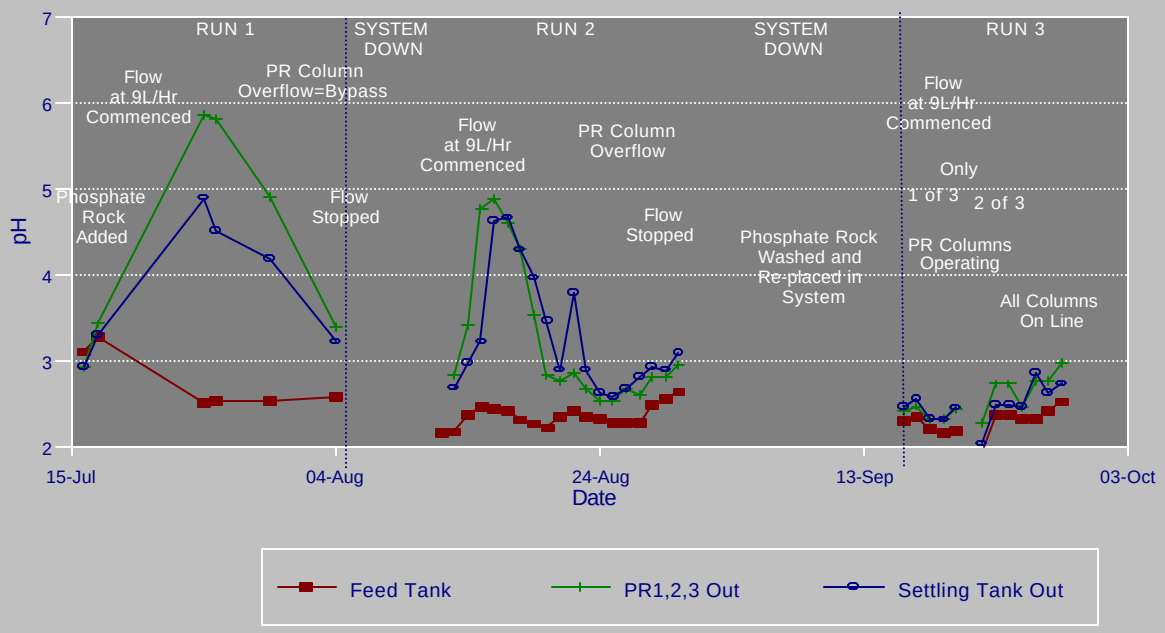
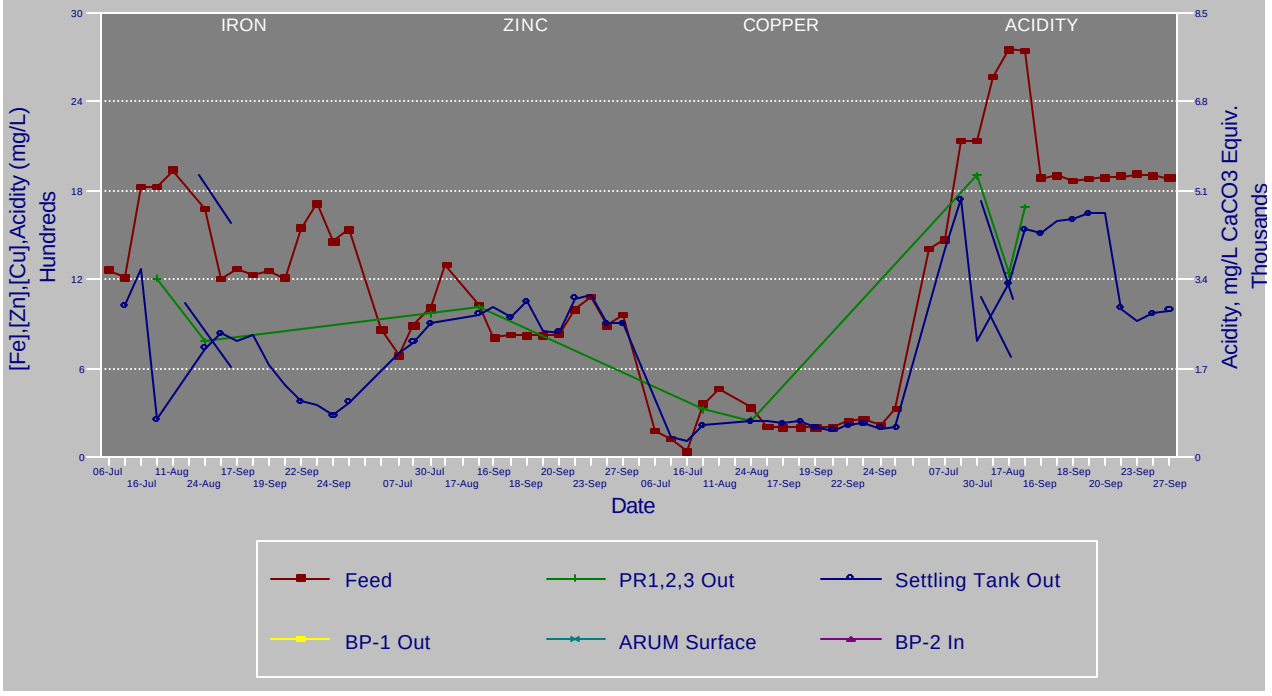


Fig.1b: Feed, PR1,2,3 and Settling Tan
[Fe], [Zn], [Cu]; Acidities



The annotation in both figures describes flow activities, plugging events and other operational details. In the first days following start-up of the first and the second runs, the pH increased from 2.5 (Feed) to as high as pH 5.7 following NPR treatment. This was expected, due to the presence of carbonates in NPR.

Overall, NPR was not supposed to profoundly raise pH, but, rather, to reduce dissolved iron concentrations and, subsequently decrease acidity. Recurrent plugging was caused by the accumulation of precipitates which were not flushed through the NPR granules, due to a combination of low flow rates and the thickness (50 cm) of the NPR layer. Because plugging occurred within 20 days in both runs, an alternate configuration of the NPR columns must be identified which flushes the precipitate from the NPR.

During Run 3, where washed NPR from Run 2 was used, the pH did not significantly increase (Figure 1a). However, iron was still removed, acidity was reduced, and the NPR did not plug before the system froze up in October.

A detailed examination of the NPR in PR-1, PR-2 and PR-3 was performed following plugging at the end of Run 1. It was noticed that the NPR had a high precipitate content, and localized fusing of granules into a hardpan. However, this concreting effect was restricted to the upper third of the NPR columns. The lower layers of the NPR column still had loose, permeable gravel.

If NPR were to be used in, for instance, a mill circuit, treatment of AMD using a design similar to a sagmill would be very effective. However, this design is inherently energy dependent, and incompatible with passive treatment systems and low-maintenance decommissioning scenarios. As an alternative application scenario, NPR might be placed in thin layers, suspended from floats. Agitation by waves would then keep the NPR sifted free of precipitates. Experiments examining the long-term reactivity of NPR, suspended in bags from floats, is currently underway.

Regardless of the precipitate plugging problem, NPR significantly changed the quality of B-2 water. Comparing water quality after treatment with water quality before treatment, the average change for all runs could be determined. The average reductions in iron concentrations and acidities of all runs of the field system were 940 mg/L of iron and 2,230 mg/L acidity ($CaCO_3$ equiv.), representing 60% iron removal and 35% acidity reduction. In Figure 1b, the data for iron, zinc, copper and acidity are plotted for all three runs. Large reductions in iron concentrations between the feed tank and the settling tank were shown. The same reductions occurred for acidity. Zinc and copper concentrations could only be reduced through co-precipitation at the prevailing pH, and therefore could not be expected to decrease as dramatically.

Copper concentrations in the feed tank were about 370 mg/L, and 130 mg/L in the settling tank (Table A1; Appendix). Uranium concentrations remained below the detection limit of 0.02 mg/L in water, and below 5 ：g/g in solids. Analytical results are given in the Appendix.

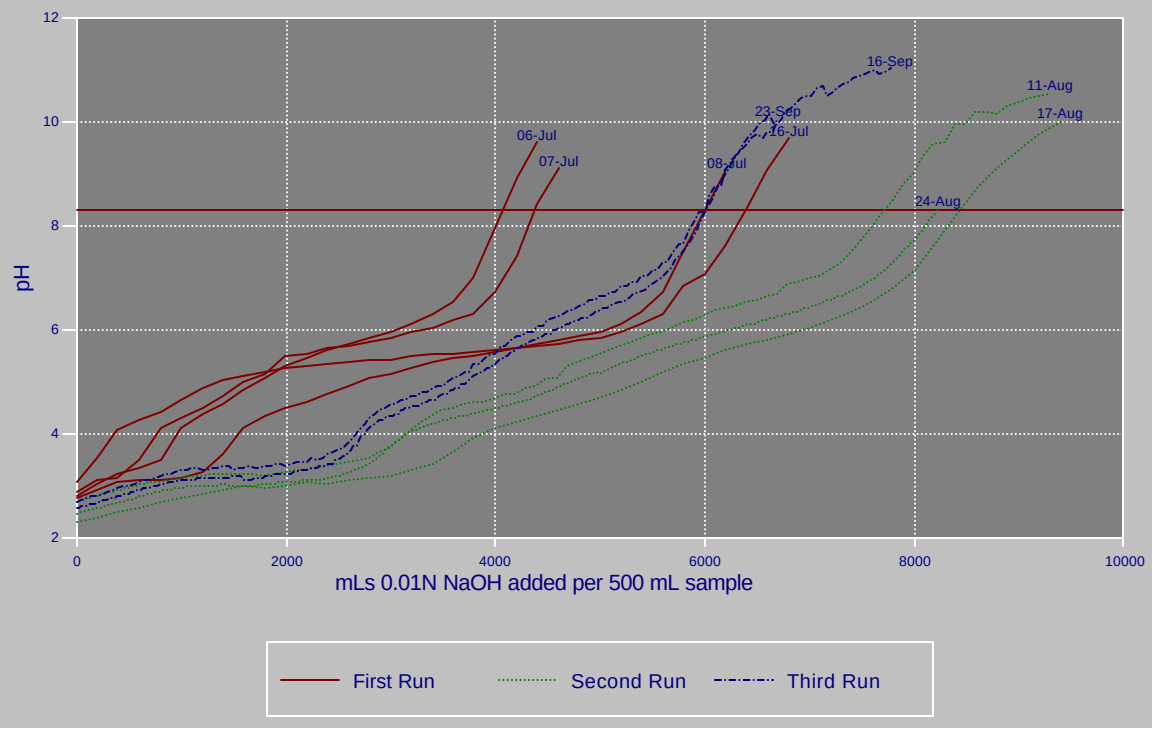
The characteristics of water leaving the settling tank and flowing through the BP-1 and BP-2 system could not be anticipated to change, because neither biological polishing systems had developed to an operational size. The results are presented in the Appendix Figures A1 and A2. However, further slight decreases in iron and acidity across BP-1 and BP-2 were recorded, likely due to residual inorganic reactions related to NPR treatment. Overall, from the performance of the field test system, significant acidity and iron reductions by NPR have been proven.

Over the course of the summer, several batches of feed water, varying in acidity, were run through the system. Because of different residence times in the various parts of the system, samples collected on the same day may have represented water from different batches. It follows that treatment efficiencies may not have been properly represented. Table A2 (Appendix) attempts to trace the exact batch of feed water for each station at each sampling

date. Thus, iron removal, calculated as an average over all three runs of the test system is probably underestimated.

The ratio of ferric:ferrous iron in the feed water changed from run to run, as indicated in Figure 2. The region of the titration curves with a low slope between pH 2.5 and 4 represents consumption of hydroxyl ions by ferric iron, while the region with a low slope between pH 5.5 to 6.5 represents consumption of hydroxyl ions by ferrous iron.

Fig. 2: Changes in Feed Water
collected from B Ditch (B2)



The acidity in the feed water increased during the course of the experiment from 4000 mg/L $CaCO_3$ equiv. during the first run, to about 8000 mg/L $CaCO_3$ equiv. in the second run. The batch of NPR which treated the high acidity in Run 2 was washed and reused in Run 3. Therefore, the last NPR batch was used to treat B-Ditch AMD for 47 days. By the end of this period, the same NPR was still treating AMD, as demonstrated by the lower acidities (Table 1).

Table 1: Field System Iron and Acidity Reduction

	Date	Feed Wate	Settling Tan	Acidity in Feed Wat		Acidity in Settling	Decrease in Acidi		Decrease in Iro	
		[Diss. Iron]	[Diss. Iron]	Total	Ferric	Total	Total	Percent	Total	Percent
		mg/L	mg/L	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	%	mg/L	%
Run 1	16-Jul	1824	1268	6400	200	5200	1200	18.8	556	30.5
	30-Jul	1820	250	6400	-	2345	4055	63.4	1570	86.3
Run 2	11-Aug	1934	-	7690	2690	-	-	0.0	-	0.0
	17-Aug	1812	130	8250	3500	3500	4750	57.6	1682	92.8
	24-Aug	1672	734	8225	2850	4595	3630	44.1	938	56.1
Run 3	16-Sep	1204	831	5640	-	4515	1125	19.9	373	31.0
	17-Sep	1266	784	5695	-	4780	915	16.1	482	38.1
	18-Sep	1226	821	5590	2500	4800	790	14.1	405	33.0
	19-Sep	1252	621	5630	-	4920	710	12.6	631	50.4
	20-Sep	1206	487	5655	-	4940	715	12.6	719	59.6
	22-Sep	1544	374	5680	-	3010	2670	47.0	1170	75.8
	23-Sep	1710	348	5720	2200	2755	2965	51.8	1362	79.6
	24-Sep	1454	281	5695	-	2895	2800	49.2	1173	80.7
	27-Sep	1532	369	5640	-	2970	2670	47.3	1163	75.9

Iron concentrations in water samples determined on-site were prone to analytical errors as large as 20%, particularly when iron concentrations were very high. This may have further added to errors in estimates of iron removal. The source of analytical errors may be the length of the delay between sampling and analysis. However, the acidities determined on-site were in good agreement with those determined in the Boojum laboratory (Figure A3, Appendix).

Run 1 feed water had a significantly lower acidity than those feed waters used in Runs 2 and 3. This explains the higher pH values in the Settling Tank following NPR during Run 1 (Figure 1a), compared to subsequent runs. However, when titration curves for feed water were compared to those for the Settling Tank (where data are available; not all samples were shipped to Boojum), acidity was reduced by passage through the NPR (PR-1 to PR-3), for the entire run. Data for the second run are presented in Figures 3a and 3b, and for the third run in Figures 3c and 3d.

Fig. 3a: Acidity Reduction in
Run 2 of Field System- August 17, 1992

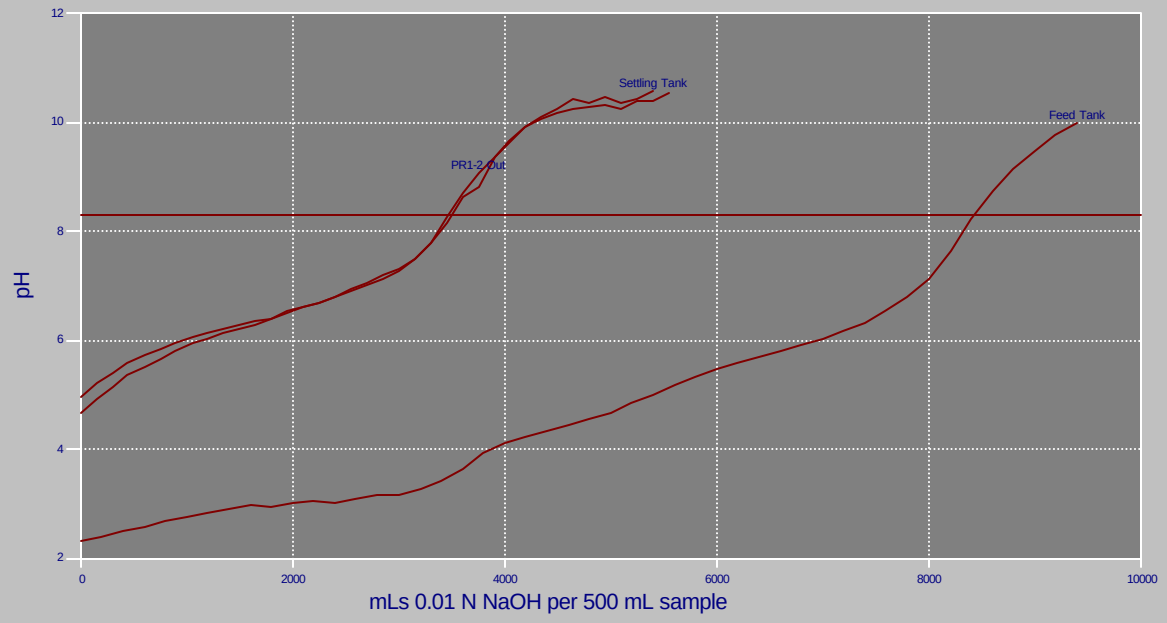


Fig. 3b: Acidity Reduction in
Run 2 of Field System - August 24, 199

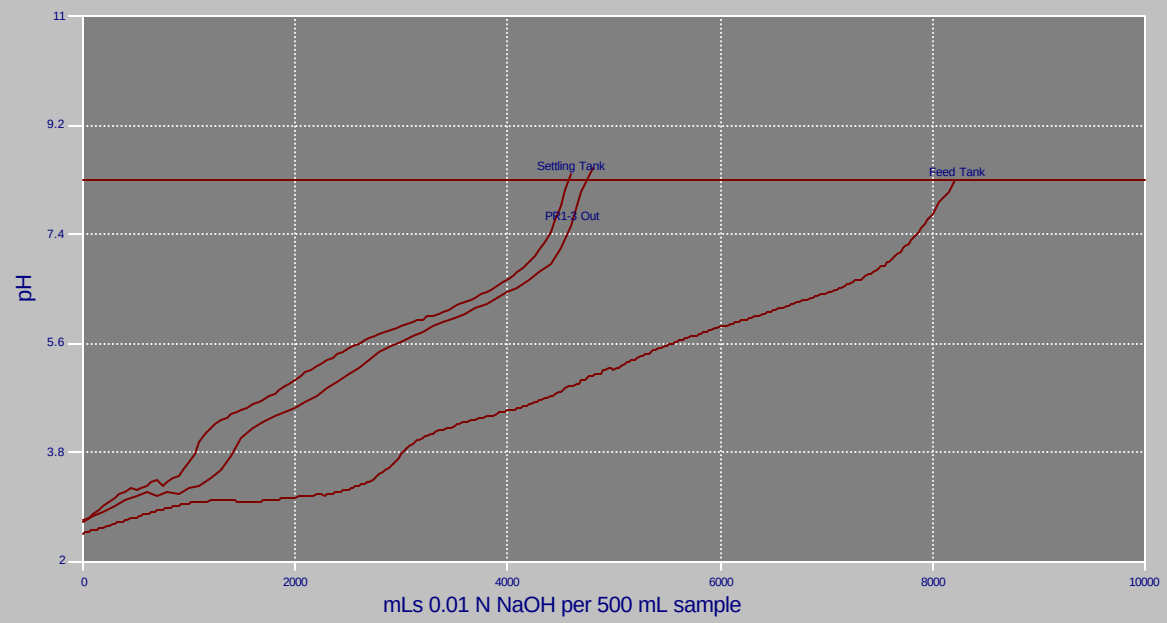


Fig. 3c: Acidity Reduction in
Run 3 of Field System - Sept. 16, 1992

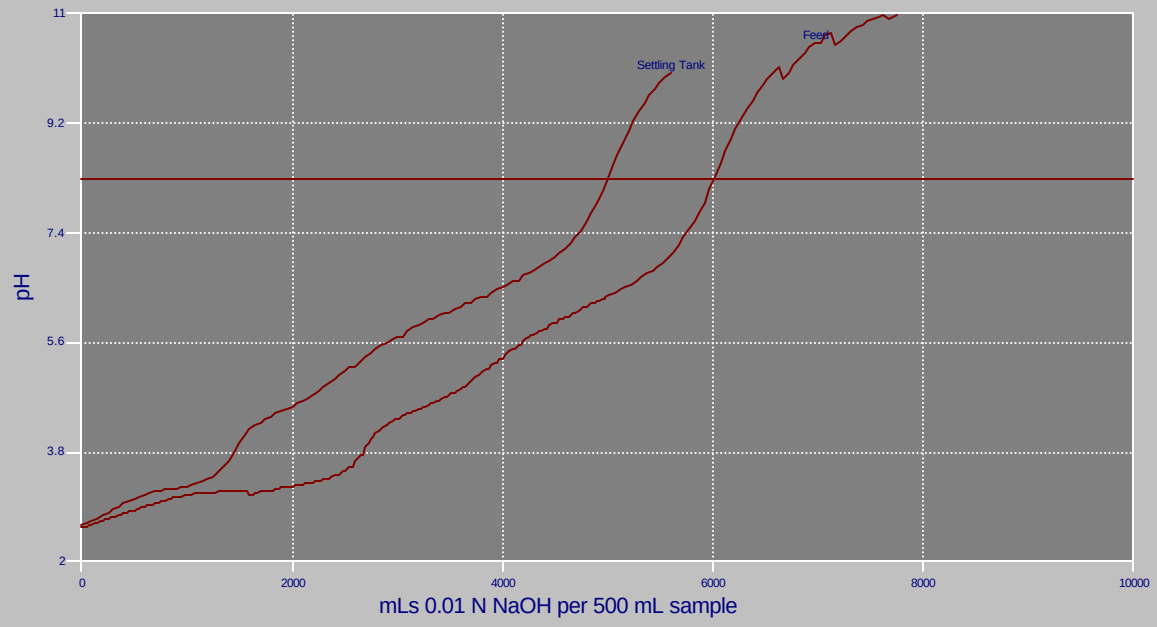
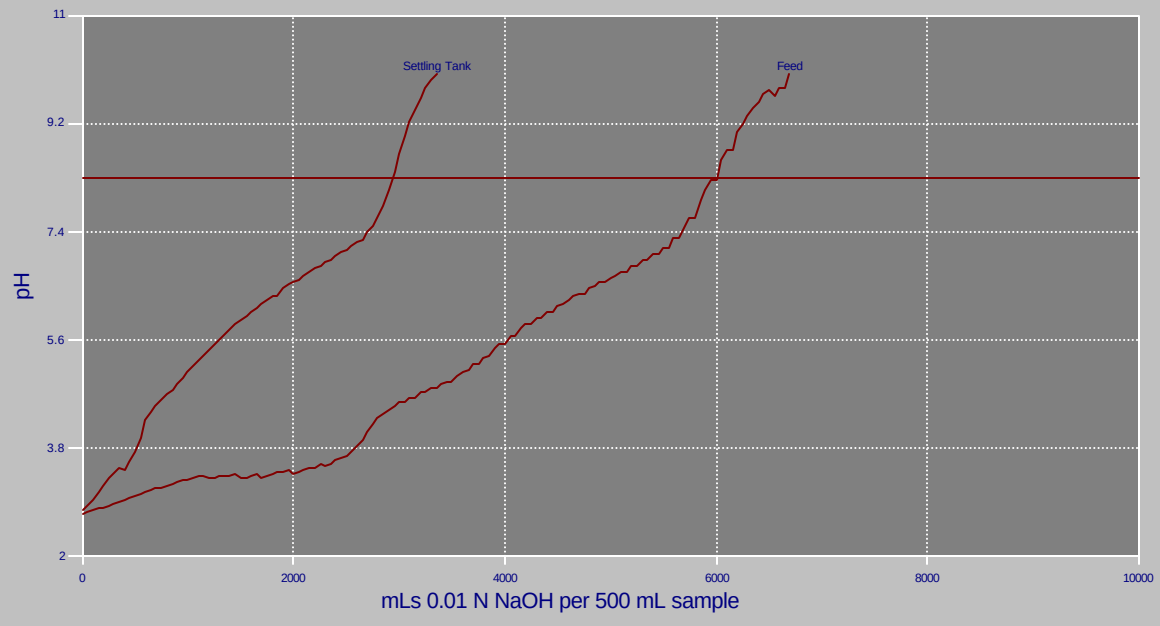


Fig. 3d: Acidity Reduction in
Run 3 of Field System - Sept. 23, 1992

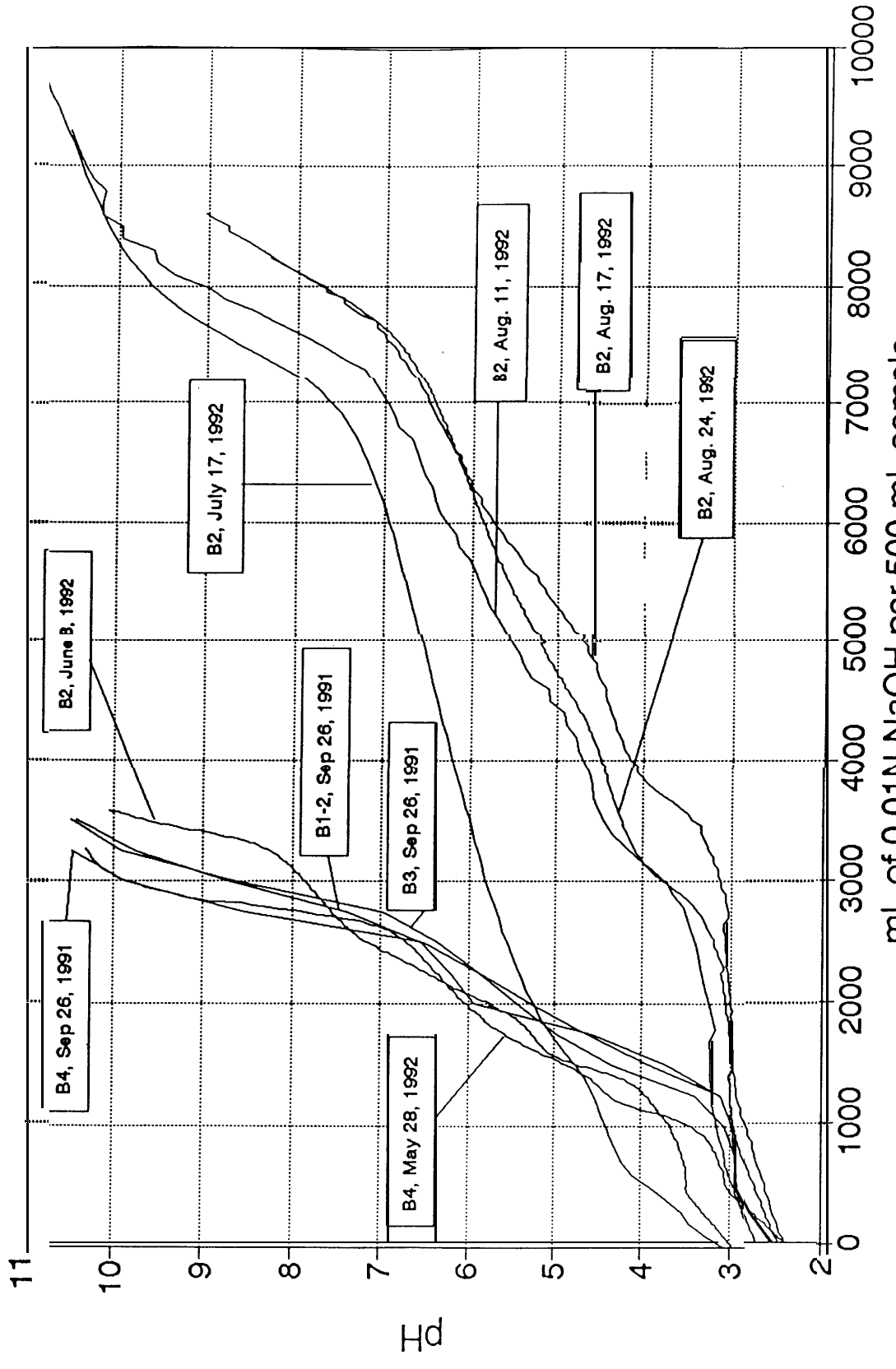


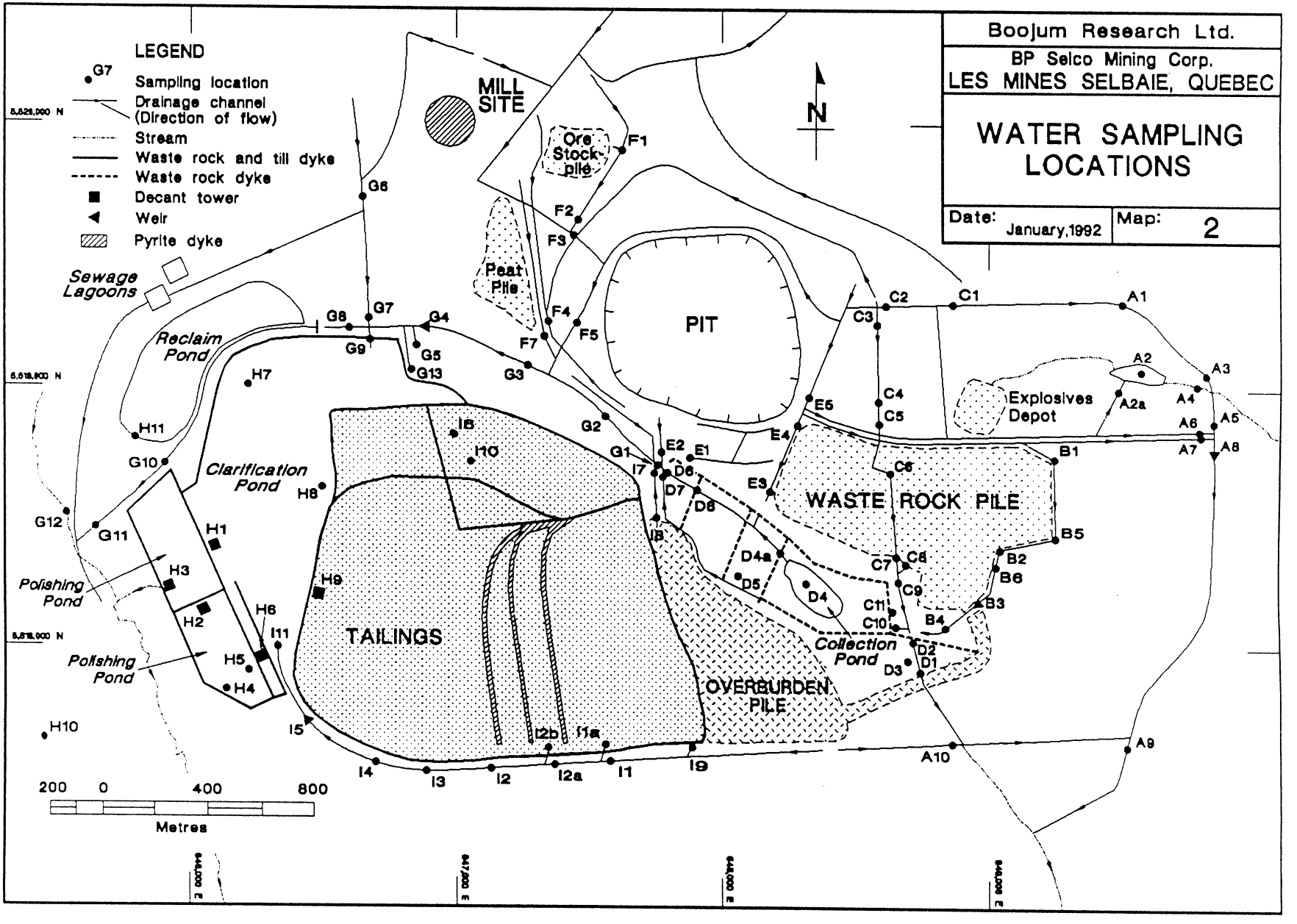
Measurements on September 23 confirmed that, although the pH after NPR treatment was the same as feed water, the acidity had still decreased, in this case from 6000 to 3000 mg/L $CaCO_3$ equiv. This NPR, used for both the second and third runs, was still effective up to the time of system freeze-up (Table 1). On the last day of sampling of the field system, 76 % of the iron, and 47% of the acidity, caused by dissolved ferric iron, were still being removed. The remaining acidity was likely due to ferrous iron and other metals dissolved in solution, such as aluminum, copper and zinc.

As the ultimate application of NPR is to treat B-Ditch water, it is essential to characterize the chemistry of B-Ditch AMD, including seasonal variation in acidity. In Figure 4, the changes in B-Ditch acidity between 1991 and 1992 are summarized. For instance, the acidity of B-Ditch water in the fall of 1991 is very similar to that in the spring of 1992. However, starting in July l992, significant increases in acidity became evident. In July and August, B-2 water had a neutralization requirement which was 2.5 times that found during the spring and the previous year.

Variation has also be noted in water chemistry between sampling locations, (B-1 and B-4; Map 2), and between seasons. At those times when AMD has exceptionally high ferric iron concentrations, even more metals will be dissolved and mobilized as AMD passes though the ditch system. This can only add to the effluent problems already encountered during the summer. NPR treatment would be beneficial in that it removes oxidized iron and reduces acidity, thereby decreasing lime requirements.

Fig. 4: B-Ditch Water Acidity
1991 - 1992




Boojum Research Ltd.
BP Selco Mining Corp.
LES MINES SELBAIE, QUEBEC
WATER SAMPLING LOCATIONS
Date: January,1992
Map: 2
LEGEND
Sampling location
Drainage channel (Direction of flow)
Stream
Waste rock and till dyke
Waste rock dyke
Decant tower
Weir
Pyrite dyke
MILL SITE
Ore Stock-pile
Peat Pile
PIT
Sewage Lagoons
Reclaim Pond
Clarification Pond
Polishing Pond
Polishing Pond
TAILINGS
WASTE ROCK PILE
OVERBURDEN PILE
Explosives Depot
Collection Pond
N
200 0 400 800
Metres

3. THE LABORATORY BENCH-SCALE SYSTEM

To complement the on-site field test system, and to examine the chemical reactions taking place between NPR and AMD in B-2 water in detail, a bench-scale experiment was carried out at Boojum. The treated water generated by the experiment was also required for growth experiments with algae.

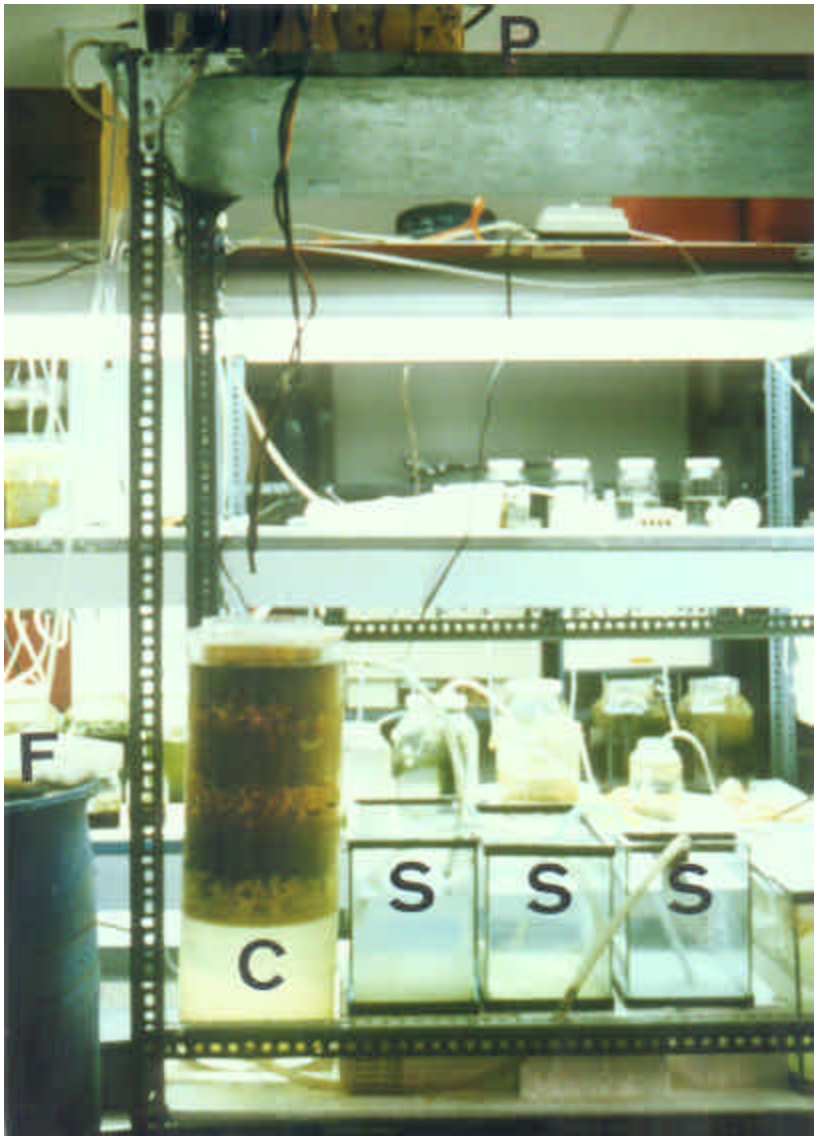


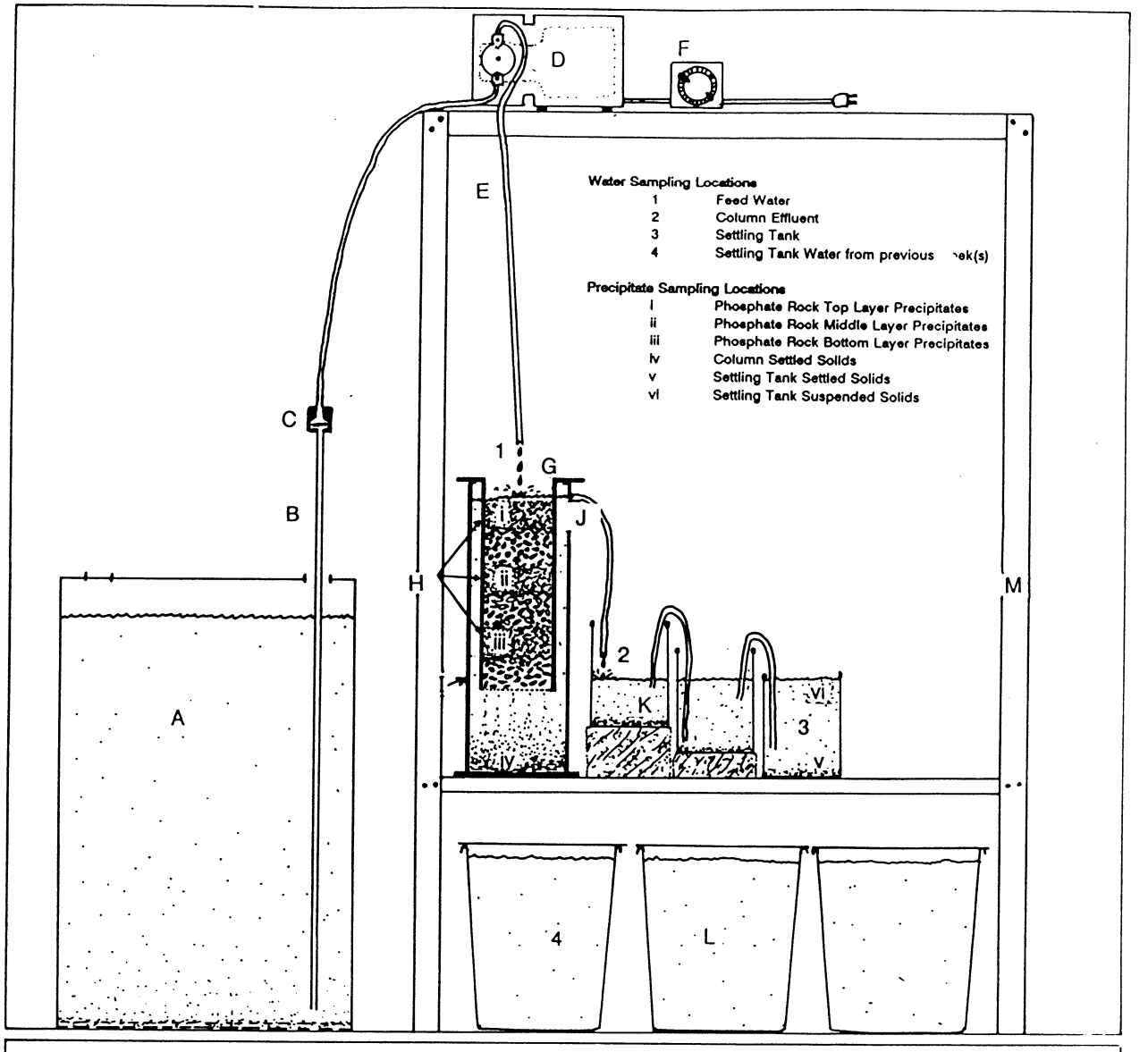
PLATE 2: Overview of the laboratory column test system. Note the layers of styrofoam chunks between the NPR layers. P, pump; C, column; S, settling tanks; F, feed water.

The laboratory experimental system design is shown in Schematic 3. A total of 4.1 kg (3 litres) of NPR (granule diameter, 3-5 mm) was packed as three layers into the inner column (H; Schematic 3 and Plate 2). The inner column had a diameter of 15 cm and a height of 42 cm. In order to prevent NPR from forming hardened, concreted layers with accumulating precipitate, each of the one litre layers of NPR was separated with a one litre layer of styrofoam packing chunks (diameter, 2.2-2.5 cm). Precipitates could settle into the large void spaces in the styrofoam. Overall, then, the column had six layers, each 6 cm thick (Plate 2).The column was suspended in an acrylic Plexiglass outer sleeve. Water level was controlled by the overflow port in the outer sleeve. The water level was just above the upper NPR layer in the column.

Water was pumped from Feed Tank A into the column. The pump, set at 50 mL/min, was controlled by a timer to operate for two 0.5 hour periods each day. Therefore, a total of 3 L per day were pumped into the column. The ratio of dispensing rate:NPR volume (3L/day:3L) in the lab system was similar to the field system (72L/day:70 L). The experiment ran for 51 days and ended when the supply of B-2 water ran out.

Water passing through the NPR-styrofoam layers in the inner column had a residence time of 0.8 days. Water drained from the inner column into the outer sleeve through a bottom sieve. The combined residence time of water in the inner column and outer sleeve was 6.8 days. Water overflowed from the outer sleeve through the overflow port (J) into a series of settling containers, as shown in Schematic 3 (K).

Most of the iron precipitates formed following NPR treatment settled in the NPR and styrofoam layers (i - iii), or at the bottom of the outer sleeve (iv). Some suspended precipitates, or precipitates formed later in the settling container (K) settled out in the settling containers. Precipitates floating on the surface of the settling containers (top, vi) were collected separately from the bottom (v) precipitates.



Lab System Components

A	200 L Plastic Feed Tank	H	Column packing. Three 1 L phosphate rock layers, alternating with three 1 L styrofoam packing chunks (cheezies). Fibreglass window screen disc placed at phosphate rock- cheeezie interface.
B	Feed Line, 4 mm I.D. rubber tube		
C	One-way valve		
D	Plastic Piston Pump, adjusted to 50 mL/min. Operates twice daily for 30 min. 3 L/day.	I	Acrylic Outer Sleeve, 20 cm diam x 57 cm tall. 18 L capacity.
		J	Overflow port, 6 mm I.D. polyethylene tubing.
E	Pump Outlet Line, 4 mm I.D. rubber tube	K	Glass aquarium 20 cm tall, 15 cm wide, 30 cm long, 9 L capacity. Three in series connected by siphons.
F	Electrical Timer, set 30 min on twice daily		
G	Acrylic Packing Chamber 15 cm diam., 42 cm tall. 6 L capacity. Perforated bottom.	L	Plastic Pails, 35 cm tall 28 cm diameter, 21 L capacity, one filled per week of operation.
		M	Steel Support Frame.

SCHEMATIC 3: Experimental Laboratory System

Each week, the inner column was dismantled, and precipitates collected from the NPR and styrofoam layers. The washed NPR was then repacked into the column. The wet, hydrated precipitate volumes were determined and dry weights of precipitates were measured.

On this seven day cycle, the system never plugged. It was run 7 times. Only moderate agitation, together with flow, would seem to be necessary to prevent plugging of the NPR layers.

Column experimental results are summarized in Table 2. The pH of the water was consistently higher following passage through the NPR. During the first 5 weeks, the pH was always higher than 4.5, and alkalinities could be measured. These increases in pH were attributed to the carbonates in the NPR. After five weeks, the available carbonate component of the NPR was likely exhausted, resulting in less of a pH change.

Table 2: Lab Column Water Characteristics

	Total Water Passed							
Date	Volume	Acidity	Alkalinity	pH	Eh	Cond.	Fe+2	Fe+3
	L	mg/L CaCO3	mg/L CaCO3		mV	umhos/cm	mg/L	mg/L
22/8	26.1	1190	4.0	5.56	265	4000	0.40	<d.l.
29/8	21.8	850	17.0	5.62	333	2700	0.01	<d.l.
5/9	18.1	825	7.5	5.40	308	2374	0.08	<d.l.
11/9	18.5	1190	8.5	4.56	335	3400	0.01	<d.l.
18/9	23.0	1235	1.5	4.63	281	3900	0.08	<d.l.
25/9	20.5	1860	0	3.52	433	4300	0.08	0.95
2/10	21.8	1975	0	3.22	359	4280	0.41	1.10
5/10	5.3	1610	0	3.04	475	3600	0.90	2.14

Iron removal was complete - both ferrous and ferric iron were completely removed. Complete iron removal occurred even after there was no change in pH. At the point of zero pH change, acidity was still being reduced from 3250 to 1610 mg/L $CaCO_3$ equiv.

In Table 3, the iron concentration and acidity reductions are summarized. Overall, nearly 100% iron removal was achieved in the bench scale column, while, on average, 67% of the acidity was removed.

The acidity titrations of feed tank water used in the experiment are shown in Figure 5. The acidity of the feed water did not significantly deviate from 3250 mg/L $CaCO_3$ equiv. throughout the experiment. Note that all of the iron in the water is in the ferric form (no ferrous step between pHs 5.5 and 7). Complete oxidation of all iron to the ferric form before treatment enhanced the iron removal efficiency of the NPR. Again, NPR was still functioning even after pH stopped rising. Iron concentrations and acidity were still significantly reduced, and NPR remained reactive after 51 days exposure to AMD (Table 3).

Table 3: Acidity Reductions during Lab Column Eperiment

Date	Settling Tank [Iron] mg/L	Feed Water Acidity Total mg/L CaCO3		Feed Water Acidity Ferric mg/L CaCO3	Settling Tank Total Acidity mg/L CaCO3	Decrease Acidity Percent	Decrease Iron * Percent
14-Aug-92	Startup	-		750	-	-	-
22-Aug-92	0.4	3535		-	1190	66.3	99.9
29-Aug-92	0.01	3543	**	1400	850	76.0	100.0
05-Sep-92	0.08	3550		1375	825	76.8	100.0
11-Sep-92	0.01	3725		1600	1190	68.1	100.0
02-Oct-92	3.04	3775		2900	1975	47.7	99.6

* Feed water iron concentration is 682 mg/L, determined by ICP on August 29 only

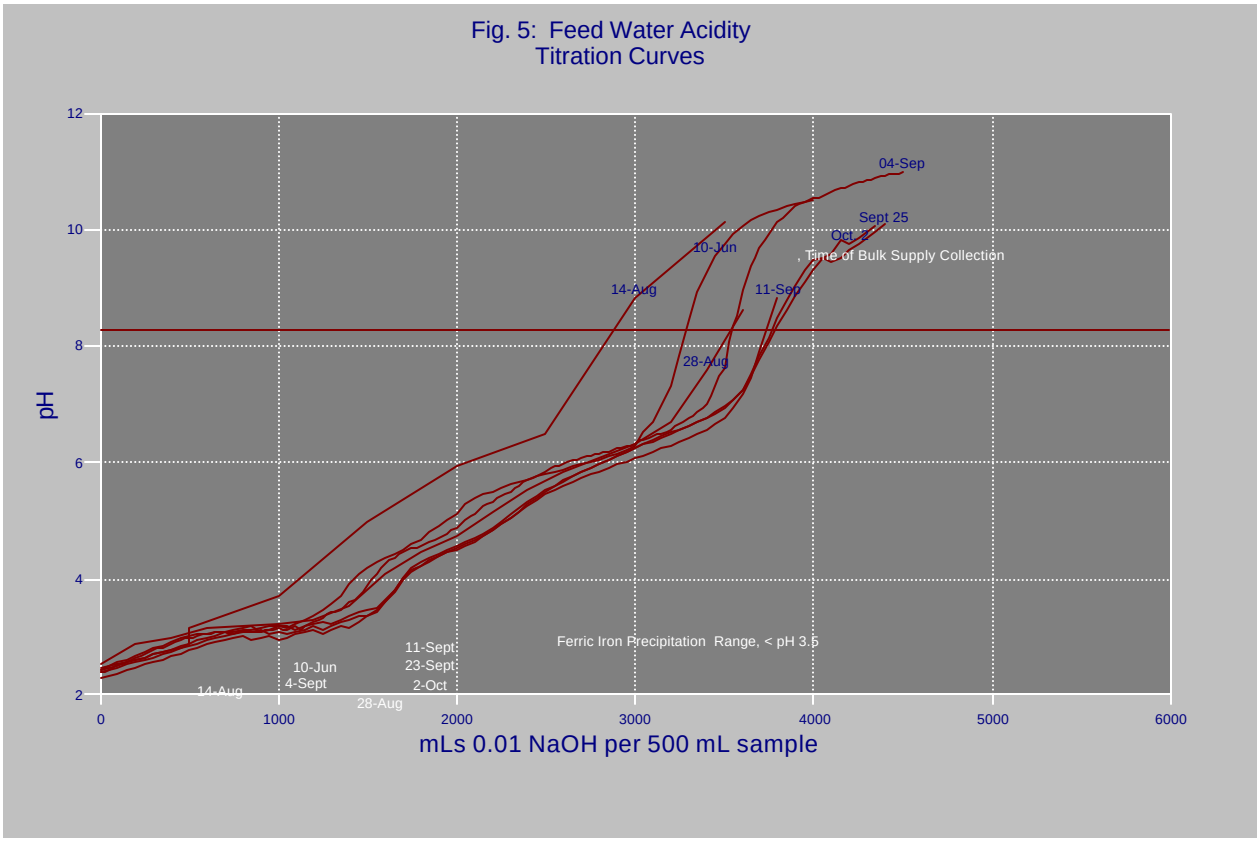
** Interpolated value (before,after)

The weights and volumes of the precipitates formed during each of the runs are shown in Table 4. More precipitate was formed per day at the beginning of the experiment. A total of 237 g of precipitates were collected from the column (Table 4) over 51 days. The weight of precipitate was not directly related to weight loss of NPR, but to a combination of precipitated B-Ditch elements and dissolution products of NPR.

Table 4: Lab Column Precipitate Quantities and Distribution

Date	1350 g NPR Layer 1 precip Colour-orange		1350 g NPR Layer 2 precip. Colour-orange		1350 g NPR Layer 3 precip. Colour-orange		Column bott. precip Colour-orange		Settling container precipitate Colour-white gree	
	Vol./mL	Wt./g	Vol./mL	Wt./g	Vol./mL	Wt./g	Vol./mL	Wt./g	Vol./mL	Wt./g
22/8	170	9.80	180	9.50	175	11.70	345	9.32	110	7.25
29/8	55	7.53	108	12.50	121	8.66	95	6.03	47	3.71
5/9	44	5.43	90	11.84	99	8.26	150	3.05	45	2.00
11/9	32	5.67	52	10.95	110	7.51	95	3.88	35	0.77
18/9	40	6.58	48	8.89	120	9.30	120	3.53	29	2.23
25/9	31	4.4	43	10.6	115	9.3	180	3.7	24	3.8
2/10	23	3.4	33	5.6	26	8.1	185	3.1	22	0.78
5/10	18	2.6	16	1.9	25	1.9	22	1.3	5	0.22
Total Wt./g		45.41		71.78		64.73		33.91		20.76

Fig. 5: Feed Water Acidity Titration Curves



After the first week's run, precipitates were settled for 0.5 h before the volume reading was taken, as a large volume of precipitates was produced. The precipitates in the remaining weeks were settled for 2 h. In the last two weeks of the experiment, a reduction in the total amount of precipitate formed was seen (Table 4).

The average solids density (g dry solids per mL fresh precipitate) of the column-formed precipitates ranged from 0.125 g/mL to 0.083 g/mL, and for the settling tank precipitates, from 0.028 to 0.048 g/mL. Although these are only relative densities, the material precipitated in the column is more dense than that formed in the settling tank.

A key observation is that 26 L of AMD produced a total of 980 mL of wet precipitate, or sludge, in the first week (Table 4), which was equivalent to 38 mL/L of B-2 water. If this is compared to the sludge volume produced with lime (raising the pH to 6), the corresponding wet, settled sludge volume is 100 mL/L of B-4 water. Therefore, not only is the sludge volume produced by NPR significantly lower than lime-produced sludge, but it is formed under more acidic conditions. Thus, during operation, the sludge volume could be reduced significantly by adding a pre-treatment with NPR, and less lime would be required to achieve the desired pH in the tailings pond.

The density (g,dry per mL, dry) of NPR did not change during the experiment. Unused NPR had a density 1.35 g/mL, while after the experiment, the measured density was 1.38 g/mL. The mass of NPR decreased over the experiment from 4.05 kg to 3.55 kg. Therefore, 12.3% of the NPR was consumed during treatment of 160 L of AMD, equivalent to 3.1 g of NPR consumed per litre of AMD.

As described above, precipitates were collected from different NPR layers, the column bottom, and in the settling tank. The precipitate which accumulated at the bottom of outer sleeve of the lab system was analogous to that precipitate which accumulated in the field test system settling tank, as both were primarily composed of iron precipitates. Similarly, the lab

system settling chambers were analogous to the Biological Polishing tank (BP-1).

In the lab settling tank, precipitate formed as a sheet over the surface of water. The precipitate was a light green, compared to the orange colour of the precipitate in the NPR layer (Table 4). It was suspected that the settling chamber chemistry was dynamic, in that further reactions were taking place in the days following contact with NPR. However, in Table 5, the stable pH values observed in the tanks indicate that these reactions did not significantly affect the pH.

Table 5: Settling Tank Water Laboratory pH Values

sample date	day 0	day 7	day 14	day 21	day 28	day 35	day 42
Aug. 22	5.56	5.88	5.74	5.04	5.29	5.40	5.27
Aug. 29		6.39	6.38	5.16	5.57	6.20	5.82
Sep. 05			5.79	5.01	5.25	5.52	5.41
Sep. 11				4.72	4.76	4.68	4.65
Sep. 18					4.63	4.48	4.34
Sep. 25						3.52	3.53
Oct. 02							3.22

The precipitates collected from the system after the first week of operation were sent for ICP analysis (Table 6). The precipitates contained mainly iron, phosphorus, aluminium and gypsum (sulphur and calcium), along with some copper and zinc. Magnesium and silicon were minor constituents.

In contrast, the precipitate formed in the settling tank contained 25 % copper, 7.9 % zinc, only 0.9 - 1 % iron, and only trace concentrations (<10 :g/g) of phosphorus. These settling chamber precipitates were likely carbonates, formed due to diffusion of carbon dioxide from the air into the water.

Table 6: Lab Column System Precipitate Analysis

ug/g precip.	Layer 1	Layer 2	Layer 3	column bot.	set.top	set bot.
Al	9260	11100	16000	31600	20600	14300
Ca	10000	18200	24100	83200	85200	125000
Cu	5360	6750	11700	35000	256000	98400
Fe	154000	132000	147000	127000	10700	9700
Mg	201	191	198	131	1100	698
P	5330	3010	3740	1550	<10	<10
S	14200	18400	24000	71200	82800	103000
Si	136	100	246	762	1103	832
U	not done	not done	not done	<5	not done	<5
Zn	1500	1970	4300	7250	79100	33000

Elements with concentrations less than 100 ug/g precipitate are not liste

Aluminium concentrations in precipitates increased from a low in the top NPR layer, to a peak in the precipitate which accumulated at the bottom of the outer sleeve. This trend is direct evidence of iron precipitation upstream at lower pHs, followed by aluminum precipitation downstream at higher pHs.

The chief product of the reaction of AMD with NPR is the formation of $FePO_4$ and $Fe(OH)_3$ precipitates. These precipitates form among the NPR granules, and are trapped in the NPR layers. The precipitates are easily rinsed from the NPR, but when trapped in the NPR layers, plug the system, posing a technical obstacle to maintaining a long-term, flow-through system. Meanwhile, solids which precipitate downstream from the NPR, will unlikely pose an operational problem, as these precipitates should easily be trapped by algae in the BP-1 component of the system. Algal biomass, in turn, sloughs from surfaces and sediments to the bottom of the polishing system, relegating the bound metal precipitates to the sediments.

Analyses of the water sampled after the first week of operation are presented in Table 7. Iron and aluminum are essentially eliminated from the water, while zinc and copper concentrations are greatly reduced. These reductions in concentrations in water corroborate with both the predicted chemical reactions, and with the composition of the precipitates. Over the effective lifetime of an NPR batch, decreasing metal removal efficiencies can be anticipated.

A mass balance was carried out on the water and accumulated precipitates for the field system during Run 1, although only a limited number of samples were available, over a 14 day period, during which 3024 L of feed water were passed through system. For the laboratory system, the analysis covered a period of 7 days, or 21 L of treated AMD, in the second week of the experiment.

Table 7: Lab Column System Water Analysis

mg/L	Feed Tank	Column Effluent	Settling Tank	Settling Tank sample 1 week old
Al	103	4.66	1.31	0.291
Ca	238	624	623	698
Cd	3.79	2.03	2.13	2.18
Cu	151	51.2	28.3	10.9
Fe	682	0.34	0.07	0.02
Mg	192	211	245	225
Mn	38.5	28	29.7	31.6
Na	7.76	14.3	15.1	13.5
P	3.83	0.83	2.44	3.01
S	1520	1040	1150	1240
Si	23.2	16	15.4	15.3
U	<0.02	<0.02	<0.02	not done
Zn	655	354	382	408

Only Cu, Fe and Zn were available for evaluation of the field system. In Table 8, the metal loadings in the feed water are presented for comparison to the loadings leaving the three NPR chambers. The total weight and elemental composition of precipitate which had accumulated among NPR granules during the operating period was used to determine that fraction of the metal loading which remained in the water, and that fraction which reported to the precipitate. Because precipitate also accumulated at the bottom of the NPR chambers and the settling tank, a fraction cannot be accounted for using the NPR precipitate alone. Overall, only 18% of the iron removed from the feed water was trapped as precipitates among the NPR granules. The detailed analysis of the precipitates is reported in Table A3 in the Appendix.

The same calculations have been performed for the lab column experiment (Table 9). The iron in the collected precipitates accounted for slightly more than 25% of the feed water iron loading.

At the time of report writing, the precipitates collected from the field system had not arrived at Boojum. It would be advantageous to generate a more complete data set of both field and lab precipitate analyses. All samples collected from the lab and field systems are currently being stored so that later analyses can be performed. In summary, loose precipitates reduce the hydraulic conductivity of NPR, they do not reduce the reactivity. Gentle agitation, as performed in the lab, was enough to "clear" the NPR. Thus, an appropriate modification for increasing agitation, or reducing "plugging" of the NPR needs to be developed.

Table 8: Field System Mass Balance Estimate

Element	Water 30-Jul-92 Feed grams	PR1,2,3 Out grams	Precipitate grams	Precipitate %
Ca			535	
Mg			2	
Na			0	
Al			114	
Cu	1077	913	37	3.4
Fe	5504	3441	991	18.0
Mn			0	
P			44	
S			220	
Si			1	
Zn	3048	2758	22	0.7

Table 9: Lab System Mass Balance Estimate

Element	Water 29-Aug-92 Feed grams	Settling Tank grams	Precipitate grams	Precipitate %
Ca	5.00	13.08	1.34	26.8
Mg	4.03	5.15	0.01	0.2
Na	0.16	0.32	0.002	1.1
Al	2.16	0.03	0.60	27.7
Cu	3.17	0.59	0.91	28.8
Fe	14.32	0.001	5.02	35.0
Mn	0.81	0.62	0.00	0.1
P	0.08	0.05	0.12	153.0
S	31.92	24.15	1.26	4.0
Si	0.49	0.32	0.01	2.4
Zn	13.76	8.02	0.27	1.9

4. BIOLOGICAL POLISHING AND ARUM PERFORMANCE

Both biological systems, the ARUM tank and the algal pools (BP-1 and BP-2) could not be made operational, as intended, due to delays in the arrival of the NPR and subsequent system construction. However, an ARUM tank was set up with untreated AMD, and algal populations from other AMD sites were introduced into the pools. The second algal introduction was successful and algae were still growing at the time of freeze up.

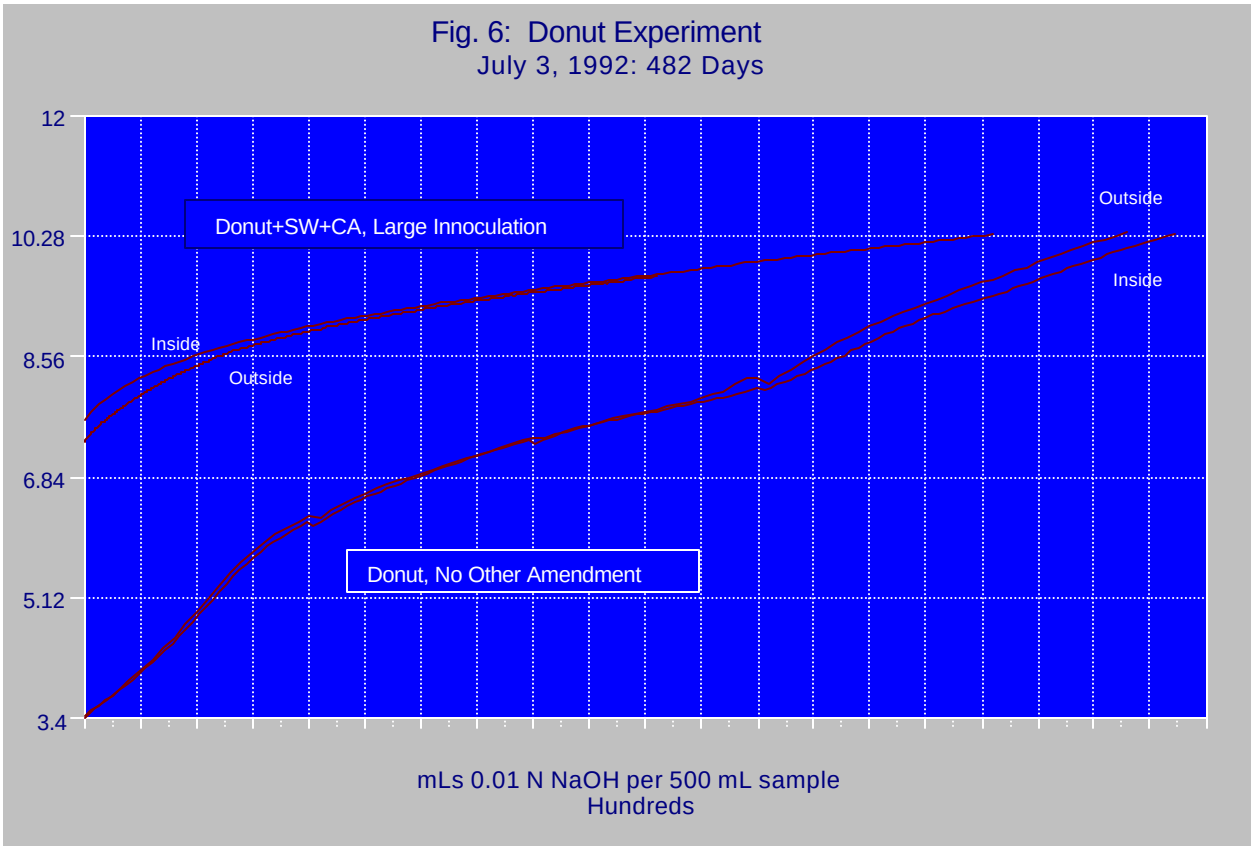
4.1 Microbial acid reduction - ARUM

The possibility of using ARUM to treat raw B-3 water with organic matter amendments was tested in the Donut experiment carried out in the Boojum laboratory, 1990-1992. In 20 L buckets, a "donut" shaped insert was created. Into the "donut hole", steel wool and compressed alfalfa pellets were placed. The "donut" itself, was filled with alfalfa hay. Finally, 18 L of B-3 AMD water were added to the buckets, and the buckets sealed.

One of the closed buckets was inoculated with sulphate-reducing bacteria, and another was not inoculated, as a control. Figure 6 shows the chemistry of the water in those two buckets after 482 days. Water chemistry was described by pH and titrations curves.

The pH in the inoculated Donut increased from pH 2.4 to 7.2. Further, acidity dropped from 5600 mg $CaCO_3$ equiv. to between 270 and 405 mg/L $CaCO_3$ equiv. All the metals were reduced to below the detection limit of < 1 mg/L in the inoculated reactor (Table 10).

These results represent the first definite proof that it is possible to create a sediment which is capable of generating alkalinity and reducing metal concentrations.



The field system ARUM tank was installed with organic amendments similar to those used in the Donuts. Haybales from the C-ditch and iron rebar were added to the ARUM tank as an inoculum. The results obtained to date in the ARUM tank are presented in Table 11. Over a period of 2.5 months, since set-up on July 6th, the pH in the middle and at the bottom of the sediment layer has steadily increased and the acidity has steadily declined. This indicates that ARUM activity has been initiated, at least in the middle and bottom sediments.

The results show that, ARUM sediment can be reproduced on a larger scale, than previously demonstrated in microcosms and in Donut reactors. Sufficient time, however, is required for initiation, particularly if AMD with very high acidities and low pH is used to start the system. If pre-treated, biological polishing water is used, the expected time for the initiation of ARUM activity, is one growing season. It is expected that, in 1993, the ARUM tank will be ready to receive BP-1 water as originally envisaged.

Table 10: Concentrations of Dissolved Elements in Lab Donuts Reactors 1 and 2 Over 483 Days Incubation

	Day 0 Raw B3 AMD 8-Mar-91	Day 1 Inside 9-Mar-91	Day 1 Outside 9-Mar-91	Day 483 Inside 3-Jul-92	Day 483 Outside 3-Jul-92
Reactor 1: Water Column Donut: Alfalfa + Steel Wool + Compressed Alfalfa + Large SRB					
pH	2.39	5.3	3.12	7.25	7.28
Cond. (uS/cm)	3000	3250	3250	6000	5900
Eh (mV)	402	-29	227	-290	-332
Acidity (mg/L)	5600	4250	4550	405	270
Elements Al	145	85	127	<1	<1
mg/L Cd	4.7	2.1	3.81	<1	<1
Co	0.74	0.61	0.67	<1	<1
Cu	180	13.8	104	<1	<1
Fe	1380	1470	910	<1	<1
Mn	53	51	50	4	4
Ni	0.33	0.29	0.3	<1	<1
S	2040	1920	2000	29	25
Zn	679	569	594	<1	<1
Reactor 2 - Water Column Donut: Alfalfa Only					
pH	2.41		2.78	3.42	3.41
Cond. (uS/cm)	2950		2800	8000	8100
Eh (mV)	405		280	114	111
Acidity (mg/L)	5900		4850	3180	3100
Elements Al	149		135	97	98
mg/L Cd	4.9		4.1	4	4
Co	0.78	not	0.68	<1	<1
Cu	190		128	61	62
Fe	1390	analyzed	837	691	668
Mn	54		49	44	45
Ni	0.33		0.32	<1	<1
S	2060		2020	2250	2300
Zn	690		681	584	594

Table 11: pH and Acidities of Solutions Sampled from the ARUM Tank at Site

	Surface Water		Top Layer		Middle Layer		Bottom layer	
DATE	pH	Acidity * mg/L CaCO3 Equiv.	pH	Acidity mg/L CaCO3 Equiv.	pH	Acidity mg/L CaCO3 Equiv.	pH	Acidity mg/L CaCO3 Equiv.
16-Jul	3.33	4000			3.58	4000		
30-Jul	4.70	1800	3.70	3180	3.67	3380	2.88	3210
11-Aug	3.41	3200	3.42	4800	3.44	5400	3.98	5000
17-Aug	3.99	3100	4.00	3650	3.83	5150	3.84	4865
24-Aug	3.92	1405	4.12	3650	3.82	3875	3.89	3400
16-Sep	2.69	765	4.10	3270	3.82	3340	3.99	2715
17-Sep	3.28	620	4.27	3545	3.87	3510	4.14	2550
18-Sep	3.00	620	4.11	3440	3.80	3330	4.11	2260
19-Sep	2.85	700	4.03	3490	3.85	3490	4.03	2325
20-Sep	2.82	695	3.96	3420	3.86	3380	4.01	2370
22-Sep	2.64	700	3.90	3410	3.56	3400	3.85	2420
23-Sep	2.95	710	4.18	3430	3.90	3260	4.19	2250
24-Sep	2.96	740	4.12	3420	3.91	3300	4.24	2170
27-Sep	2.83		3.91	3615	4.03	3320	4.37	2350

* Tank filled with B3 water after bonemeal treatment (pH 2.92, Acidity 4200) on July 6, 19

Detailed chemistry of two sets of ARUM samples is given in the Appendix (Table A4 and Figures A4a to A4c). At the low pH values which still prevail in the ARUM tank, a reduction in the concentration of contaminants cannot be expected, although the copper concentrations of water in all layers were reduced.

4.2 Biological Polishing in BP-1 and BP-2

Algae are an integral part of the decommissioning scenario, as they are required to remove precipitates and some dissolved metals after NPR and after ARUM. Algae provide a "sticky" surface on which precipitates can be sieved or formed, and on which dissolved metals will bind. As a biological system, they can also remove phosphorus, which is used as a growth nutrient. After death, the biomass will sink to the bottom and provide carbon to the sediments.

Three parameters must be addressed concerning the operation of the biological polishing system. First, populations of algae which survive and grow in pre-treated B-3 water must be identified. Second, the growth rate of these algae must be determined, and third, their capacity to remove excess phosphate and metals must be measured in order to calculate the size of the population required for effective operation of Biological Polishing system.

In 1990 and in the beginning of l991, macroscopic algal populations were present in the first cell of the collection pond. However, since then, the characteristics of B-ditch water deteriorated to such a degree that the indigenous algal community has been reduced to only species of unicellular algae. Since these microscopic species are not effective in terms of biological polishing, an alternative source of macroscopic algae was sought.

Algal biomass was collected from two other acid mine drainage sites and introduced to the Biological Polishing pools. The field conditions supporting these algae, as well as other algae used in the lab experiments, are listed in Table 12a. Biomass of *Ulothrix*, a species colonizing the South Bay site (N.W. Ontario) was introduced to BP-1. The algae, however, did not survive, even though the original population had a demonstrated ability to grow in relatively low pH-high metal content water.

A second introductory trial was attempted using *Zygogonium* biomass; this material was collected from a population at a second northern Ontario mine site, where acid mine drainage has a similar pH (2.2) and acidity (5300 mg/L $CaCO_3$ equiv.) as B-Ditch water. This batch of algae, introduced to BP-1 shortly after August 27, 1992, was still growing when precipitate was sampled on October 14, 1992. Therefore, an algal species capable of growing in NPR-treated water has been identified. Growth and polishing capacity of the algae were determined in laboratory experiments, performed concurrently with the operation of the field test system. In total, 6 experiments were carried out in the laboratory. The *Ulothrix* species from South Bay was used in growth experiments 4 through 6, while the *Zygogonium* species was used in experiment 2. The results of these laboratory growth experiments are summarized in Table 12b.

Table 12a: Field Population Characteristics, Biological Polishing

	TAXON	ORIGIN	pH	ACIDITY mg/L CaCO3
EXP 1	Mixture	Lab	6	50
EXP 2	Zygogonium	N. Ontario	2.2	5300
EXP 3	Ulothrix	Nova Scotia	3.5	900
EXP 4	Ulothrix	N.W. Ontario	3.5	500
EXP 5	Ulothrix	N.W. Ontario	3.5	500
EXP 6	Ulothrix	N.W. Ontario	3.5	500

Table 12b: Results of Biological Polishing Growth Experiment

	RGR*	DENSITY	pH	AERATION	LIGHT**
	% increase per day	g/L		CONT/INTER.	uE/m2/s
EXP 1	0	1.5	4.9	INTERM.	250
EXP 2	-0.1	1.6	2.3	INTERM.	250
EXP 3	1.4	2	4.4	CONT.	250
EXP 4	7.5	0.2	6.3	CONT.	250
EXP 5	8.7	0.2	5.8/6.6	CONT.	420
EXP 6	6.5	0.2	5.6	CONT.	420

RGR - Relative Growth Rate

: E/m^2/s is the S.I. unit for light intensity; one micro Einstein (: E)/m^2/s = 6.02 x 10^{17} photons/m^2/s.

The first three experiments employed a methodology where a large amount of algae must be added, and the culture permitted to grow for a long period of time, before reliable growth rates can be determined. The set-up of the high biomass experiments is depicted in Plate 3.

Low relative growth rates, amounting to no more than a 1.4% increase in biomass per day, were determined in these trials. Using this methodology, slower relative growth rates can be expected, since nutrient supplies to the algae can become limiting during the growth period, while the algal biomass itself blocks light. In the field, these conditions can prevail in a population that has reached maximum density in a low flow regime.

PLATE 3: High density algal growth experiments.

During experiments 4, 5 and 6, a new methodology was employed, which provided growth conditions more similar to those experienced by small amount of biomass colonizing a large flowing system, such as a Biological Polishing pool. Only a tenth of the algal biomass added during the first experiments was added during Experiments 4, 5 and 6, and growth was monitored over a shorter period of time. In these experiments, relative growth rates of up to 8.7% increase in biomass per day were measured (Table 12b).

Phosphate concentrations were monitored during experiment 4, where algae were grown in NPR-treated B-Ditch AMD. Phosphate uptake rates, ranging from 130 to 170 :g phosphorus per gram algae per day, were calculated using the measured phosphate content of the algae (1,765-2,215 :g phosphorus per gram dry weight of algae) and the relative growth rate. During the same experiment, metal concentrations in the algal biomass, sampled at the end

of the growth period, averaged 14,200 µg per gram of algae. The zinc uptake rate was therefore 1,070 µg zinc per gram of algae per day.

During operation of the field test system, approximately 300 mg of phosphorus (in 216 L of water) passed through Biological Polishing pool 1 each day. From the above estimates, a 30 kg algal population would be required to produce the 2.3 kg of new biomass per day needed to remove the phosphorus.

If, for example, 10,000 mg of zinc precipitate (50 mg suspended zinc/L) passed through the system per day, a 125 kg algal population would be required to produce the 9 kg of new biomass needed per day, to remove all the suspended zinc. According to the estimated algal growth rates, a two to three month growing period would be required to achieve this algal biomass, if the population was started using a 500 g inoculum.

Overall, the field and laboratory experiments have, first, identified a species of macroscopic algae which will survive and grow in NPR-treated B-Ditch water, and second, demonstrated that a relatively small population can remove any excess phosphorus. Finally, a relatively dense algal population in the Biological Polishing pools will have to develop before suspended metal concentrations are substantially reduced.

5. WASTE ROCK EXPERIMENTS

5.1 Experimental Design of Waste Rock Set-up

Waste rock dumps are significant sources of acid, generated by the oxidation of sulphides within the dump. Oxygen and water supply are oxidation rate-controlling factors, and oxygen supply is the reaction-limiting component.

If secondary minerals can be formed on the surface of the rocks, then acid generation might cease. Evidence for this proposition comes from the Gibraltar waste rock pile, which was used as a heap leach. It ceased to function and no longer produced either metals or acid. When the pile was investigated, it was noted that the rock was covered with secondary minerals. Several rock samples from inside the Gibraltar pile have been obtained by Boojum Research and will serve as a comparison, when secondary mineral formation in the waste rock experiment is being evaluated.

A laboratory experiment was set up to:

- quantify oxidation in waste rock
- determine the interactions of NPR with waste rock
- address secondary mineral precipitation on the rock.

It is impossible to simulate the conditions within a waste rock pile. However, the following considerations were taken into account. Waste rock piles consist of lifts onto which NPR, either spent, from iron precipitation, or fresh, is to be placed. The uppermost layer of each lift (0.05-0.1 m thick) is very compacted, due to haul truck and bulldozer activity. Therefore, an assumption is made that the NPR, distributed as a thin layer (0.05 m) on top of the lift, would not trickle into the pile.

After completion of the next lift on the pile, there would be a NPR layer over the original lift inside the pile, receiving AMD from the overlying lift, after it has percolated through the NPR layer. By the time a final application of NPR is added to the surface of the final lift, acid generation will have already started in the older lifts. Therefore, two series of chemical reactions will occur within the waste rock pile.

In the first series of reactions, water (rain, snowmelt) percolating through the waste rock solubilizes the products of rock oxidation. The resulting acidic, metal-contaminated water (AMD) continues to percolate downward to the NPR layer, where the solution reacts with the phosphate, carbonate and calcium, and precipitates are formed.

In the second series of reactions, the NPR-treated water, carrying phosphate, carbonate and sulphate precipitates, continues to percolate through the next bench of waste rock. The residual alkalinity in solution, combined with the solid precipitates, will coat waste rock surfaces and form secondary mineralization.

Both series are simulated in the experiment, as depicted in Schematic 4a and 4b. In the first configuration, a 0.05 m layer of NPR was used at the ratio of thicknesses at which NPR would be applied (thickness NPR: thickness of bench). As comparable compaction is not possible in the drums, compaction was simulated by inserting a horizontal screen in the drum between two waste rock layers. This represents the interphase between the bench receiving AMD/NPR water (Schematic 4a) and pure AMD.

In the second configuration (Schematic 4b), the screen is positioned at the bottom of the rock layer, while the NPR is applied to the top, at the same application rate of 0.05 m.

A total of 17 drums were set up outside the Boojum laboratory (Plate 4). The waste rock in each drum is underlaid with a layer of styrofoam blocks to facilitate drainage (Plate 5). Sampling ports extend to the bottom of the drums. Overflow drains positioned at the

styrofoam - waste rock interface have been installed to remove excess water, so that waste rock overlies, but is not soaking in, AMD (Schematic 5).

Principal hypogene minerals in the rocks are: pyrite, sphalerite and chalcopyrite. Galena, tetrahedrite, polybasite and native silver are encountered in minor amounts; native gold in trace amounts. Host rock is comprised of dacite tuff and rhyodacite breccia which is non-acid generating. These rocks are derived from andesite, which will also be encountered in the type D rock collection. Generally, these rock types are not deposited into the waste rock pile, but used for construction.

The waste rock experiment was set up with different types of rocks, representing different ages of weathering. On site, they are referred to as:

a) low pyrite rock, which is deposited on the waste rock pile;

b) non-acid generating host rock, which is sometimes deposited in the waste rock pile, or is used for construction, and

c) high pyrite rock, which is deposited into the tailings area.

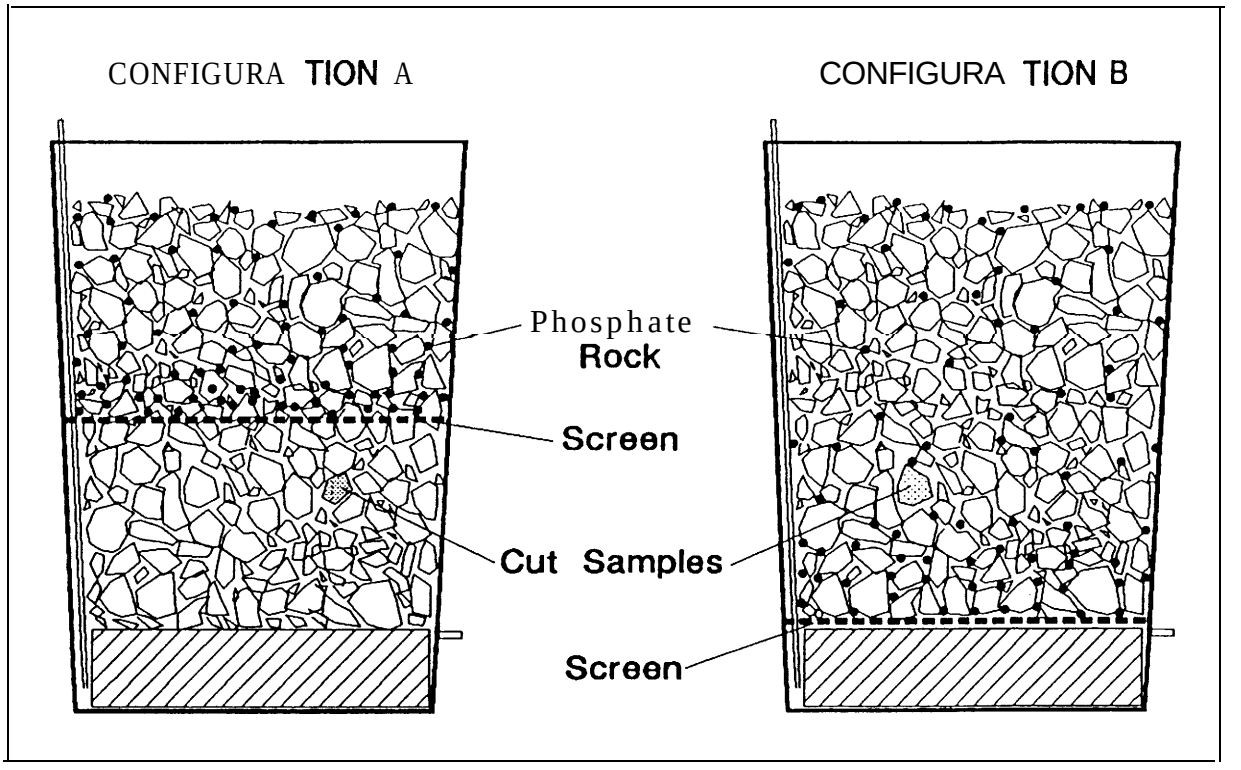
Rock samples were collected at Les Mines Selbaie at locations indicated in Map 3. The stage of weathering of the rock type collected, or lengths of exposure of the waste rock, was confirmed with the chief geologist. The characteristics of the rock types are as follows:

Type A - low pyrite fresh waste rock, which was weathered for one winter (from the pit at the end of 1991 or early 1992).

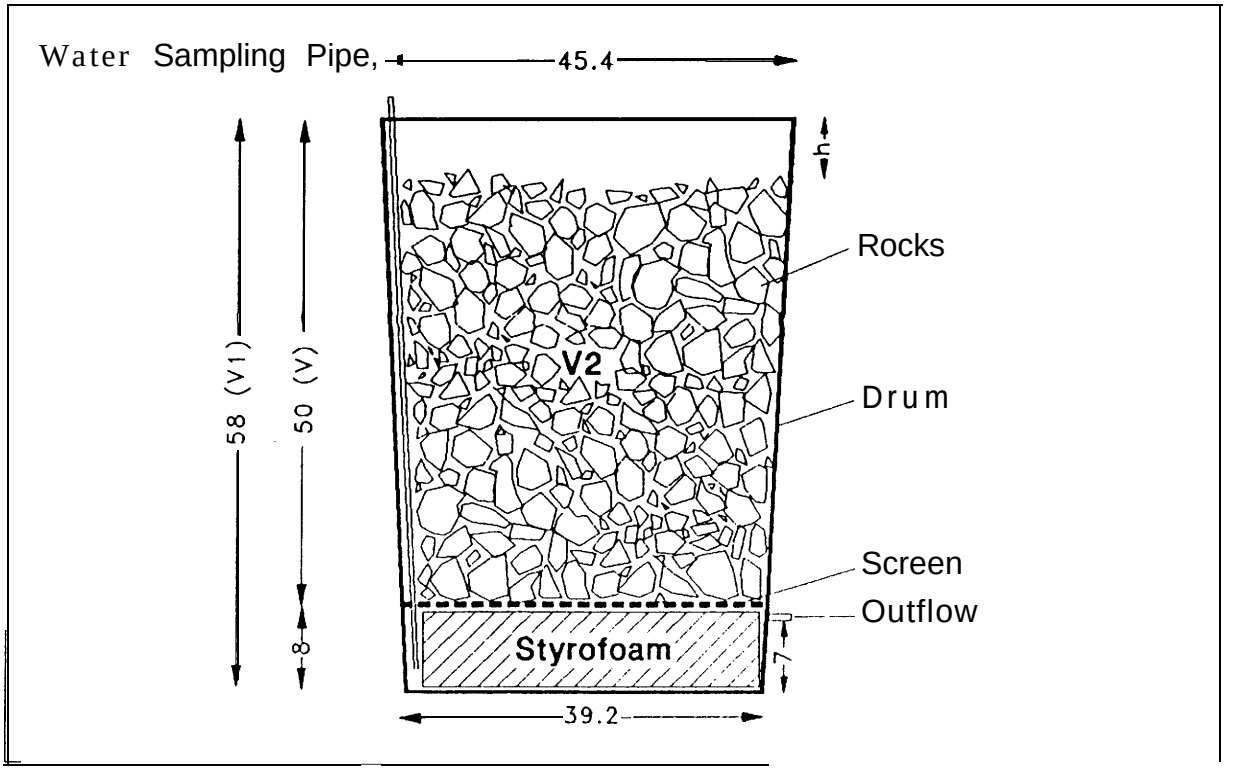
Type B - high pyrite fresh, dumped within the months of collection.

PLATE 4: Partial view of the waste rock experiment during set-up.

PLATE 5: View of bottom section of a waste rock drum.



Schematic 4: Location of phosphate rock layer in drums.



Schematic 5: Drum construction (dimensions in cm).

Type C - low pyrite with high fraction of dacite tuff; weathered for 4 or more years.

Type D - essentially dacite tuff, about 1 year old.

Type E - high pyrite old, low grade ore, weathered for 4 or more years.

Four drums were built for each type of rock, except for type D, which was classified as non-acid generating rock. This results in the following configuration, where X (A, B, C, D, E) indicates the rock type.

Drum X-1, control drum without NPR, 1 thin section.

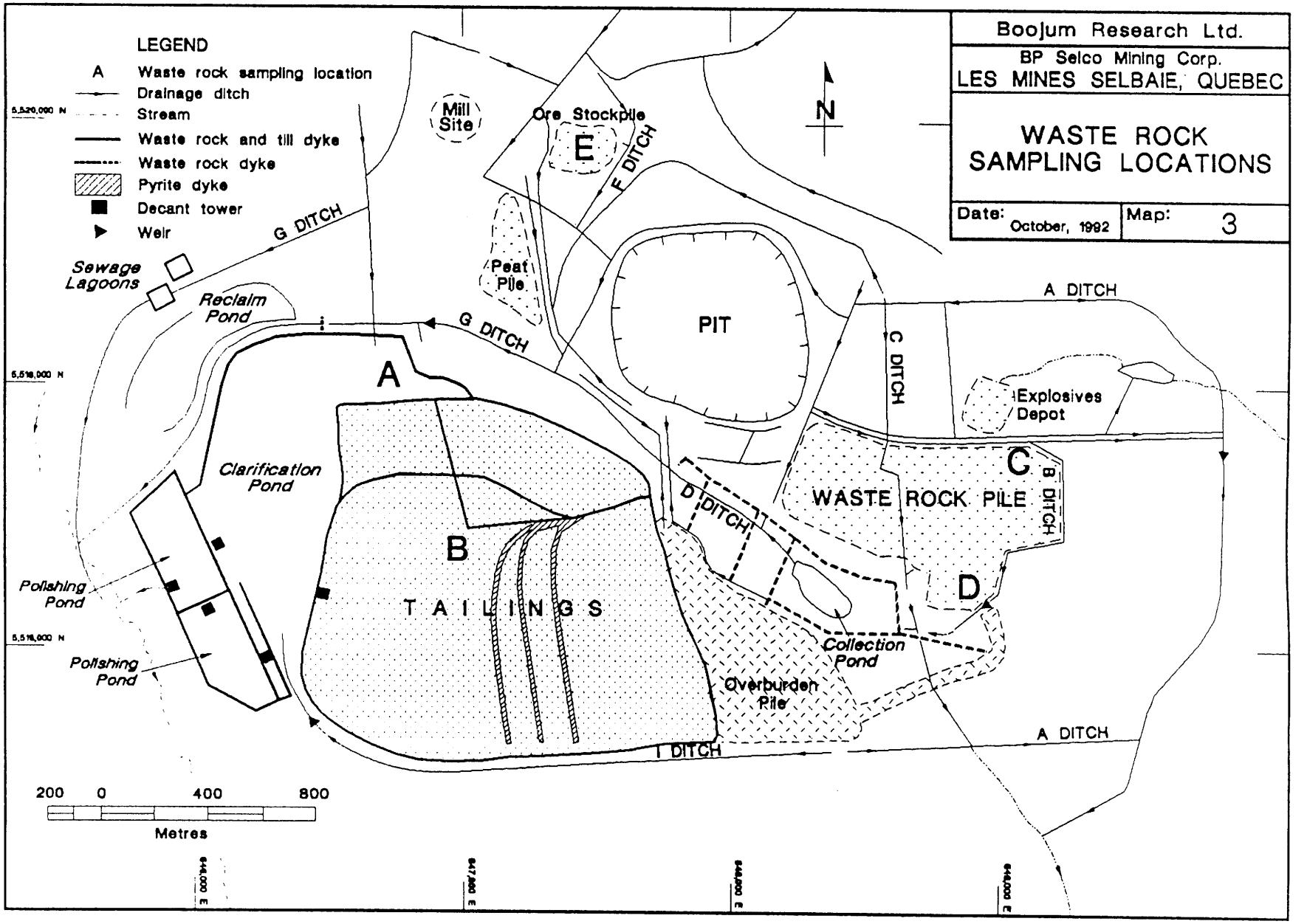
Drum X-2, treatment drum, net and NPR on the styrofoam support at the bottom of a drum; samples in contact with NPR (3.6L equivalent to 0.05 m layer).

Drum X-3, treatment drum, net and NPR approx. 0.30 m above the styrofoam support, between rocks; samples below net, no contact.

Drum X-4, prepared for treatment with spent NPR, which is not available.

Drum D-1 is a control drum, containing 30% of type C and 70% of type D rock. This ratio was provided by the chief geologist as the ratio representative of non-pyritic material to pyritic material which comes out of the pit. Hence, drum D-1 simulates the unsegregated waste rock. It will be used to assess the relative importance of non-acid-generating material in the waste rock pile.

In order to quantify the surface oxidation of the rocks, 99 rocks were cut; one-half of each rock was inserted into a drum containing the same type of rock. The other half is being stored in nitrogen, for comparison at end of the experiment. The location of the cut rocks are marked on the outside of the drums. It is therefore possible to remove the cut rock



WASTE ROCK TYPES: A: Low pyrite fresh, B: High pyrite fresh, C: Low pyrite with high fraction of dacite tuff D: Essentially dacite tuff, E: High pyrite old

from a drum without disrupting the rock configuration. It is expected that, initially, the first group of rocks will be removed for examination after one year. Further removals will depend on the results obtained after the first year.

In addition, a thin section of each type of rock was prepared and a photographic record was made at low magnification. They were also placed into the drums and can be retrieved. It is planned to remove the thin sections after six months, when there is some indication that NPR is affecting effluent water chemistry. SEM and EDS of thin sections should depict stages of oxidation retardation or other reactions which have taken place on the surface. Thin sections will be made parallel to, and perpendicular to, the cut sample surface, to observe the magnitude and range of the oxidation process.

Void ratios of rock in each drum were determined and are given in Table 13. The void ratio represents the ratio of the volume of water drained from a drum filled with rocks, to that of the bulk volume occupied by rocks. In Plate 6, the average rock sizes used in the experiment are shown. The ratios achieved for all 18 drums were a minimum of 41.2, and a maximum of 47.8, a relatively narrow range.

Water samples are being taken from each drum, either from the overflow or from the drum bottom. Sample collection on a weekly schedule is currently being performed to establish the onset of acid generation, although continuance of this frequency will be assessed after significant acid generation has taken place. Acidity titrations have been carried out on the water from the drums, along with determination of pH, Eh and electric conductivity. Rain water has also been collected and analyzed.

The monitoring data for the experiment are presented in Table 14. The two control drums, D-1 and C-1, started generating acid after 22 days, as shown by increased conductivity and slight decrease in pH. Acidity titration curves for water from all drums are presented in Figure 7a for September 22nd, and in Figure 7b for October 1st.

Table 13: Waste Rock Experiment

Void Ratio

Drum#	h cm	V2 L	V3 L	RATIO V3/V2	RATIO %
A-1	14.2	48.29	20.00	0.41	41.42
A-2	13.7	49.04	21.70	0.44	44.25
A-3	15.1	46.94	20.50	0.44	43.67
A-4	12.2	51.30	23.30	0.45	45.42
B-1	13	50.09	22.80	0.46	45.52
B-2	10.7	53.58	25.65	0.48	47.87
B-3	12.9	50.24	21.80	0.43	43.39
B-4	11.43	52.47	22.23	0.42	42.36
C-1	15.3	46.65	21.80	0.47	46.73
C-2	13.4	49.49	21.60	0.44	43.65
C-3	15.4	46.50	20.00	0.43	43.01
C-4	13.6	49.19	21.80	0.44	44.32
D-1	14	48.59	21.20	0.44	43.63
E-1	13.8	48.89	22.20	0.45	45.41
E-2	11.2	52.82	23.20	0.44	43.93
E-3	8.7	56.65	25.48	0.45	44.98
E-4	11.2	52.82	23.30	0.44	44.12
AVG					44.33

Note:

Dimensions of each drum:

High [cm]	50.00
Top radius [cm]	22.70
Bottom Radius[cm]	19.62

h - distance [cm] to water leve

V - Total volume of the drum | 82.16

V1 - Used volume of the drun 70.40

V2-Volume of the water and rocks[L] V2=V2(h)

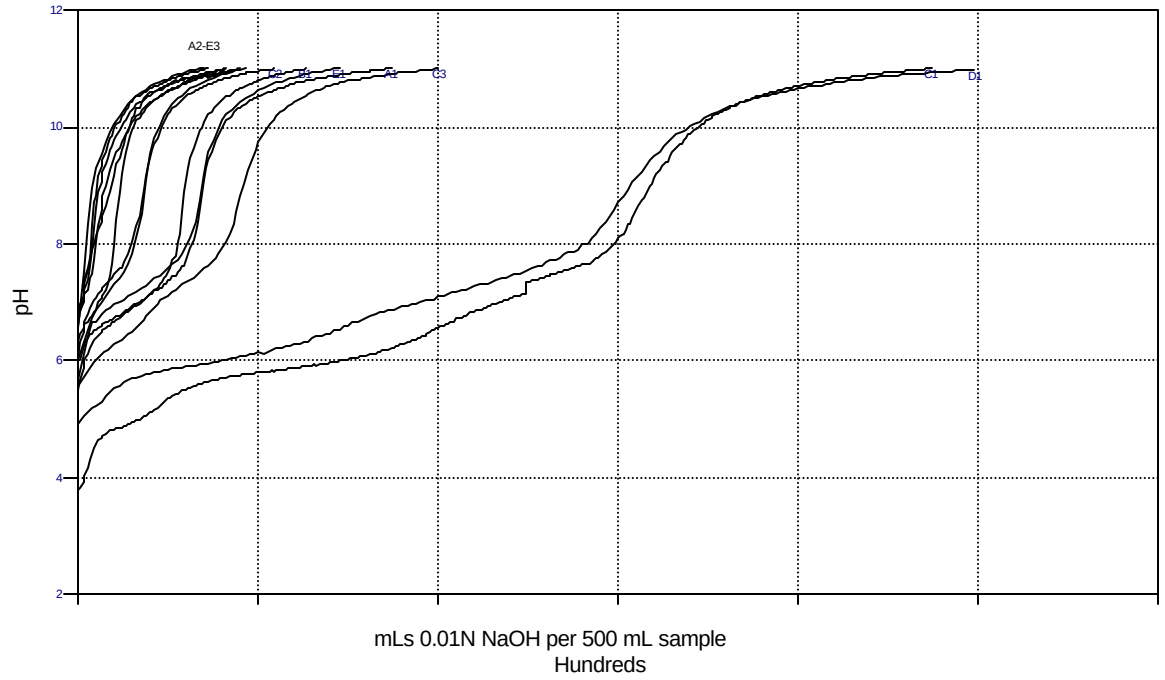
V3 - Volume of drained water [L]

Table 14: Waste Rock Experiment Started on August 25*/26, 1992

pH and Electric Conductivity

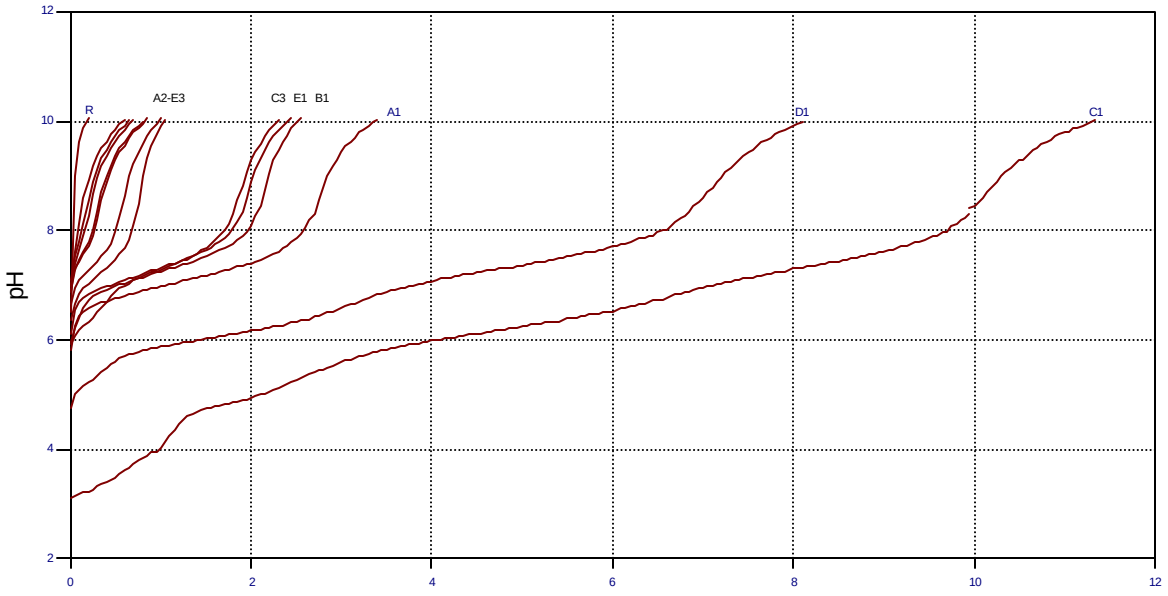
		September 01/92		September 18/92		September 22/92		October 01/92	
	PO4		Corr.		Corr.		Corr.		Corr
Drum#	Rock	pH	Cond.	pH	Cond.	pH	Cond.	pH	Cond.
	L		umhos/cm		umhos/cm		umhos/cm		umhos/cm
A-1		6.48	362	5.54	800	5.88	700	5.59	600
A-2	3.6	6.39	430	6.12	800	6.17	710	6.87	700
A-3	3.6	6.66	390	6.43	880	6.23	705	6.76	550
A-4		6.50	390						
B-1		6.66	378	6.01	600	5.6	500	5.95	490
B-2*	3.6	6.48	415	6.34	870	6.19	795	6.9	650
B-3*	3.6	6.50	470	6.42	860	6.4	900	6.95	800
B-4		6.44	440						
C-1		6.54	350	4.79	1050	3.85	1200	3.08	1300
C-2	3.6	6.47	390	6.19	970	5.66	905	6.34	750
C-3	3.6	6.40	330	5.84	100	5.38	990	5.73	950
C-4		6.44	370						
D-1		6.47	350	5.12	1060	4.69	1100	4.59	880
E-1		6.68	300	5.78	350	5.51	349	5.86	350
E-2	3.6	6.52	320	6.35	580	6.14	520	7.03	530
E-3*	3.6	6.50	285	6.18	680	5.95	540	6.57	530
E-4		6.52	295						

Fig. 7a: Waste Rock Experiment
September 22, 1992



mLs 0.01N NaOH per 500 mL sample
Hundreds

Fig. 7b: Waste Rock Experimet
October 01, 1992



mLs 0.01N NaOH per 500 mL sample
Hundreds

Initially, the acidities in both C1 and D1 were quite similar, due to the presence of ferrous iron, evident from region of the curve with a low slope between pH 5.5 and 7. By October 1st, C1 had definitely released more dissolved iron, and lowered the pH, as oxidation proceeded. Comparing the titration curves of the remainder of the drums on October 1st, all types of rocks, A, B and C, are changing the water draining through the drums. The controls, or X-1s without NPR, are the greatest acid generators thus far. The results suggest that NPR may already be retarding acid generation. The carbonate component of NPR is expected to react slowly as only rainwater (R; Fig. 7b) is entering the drums. It would be advantageous to add more drums to the experimental design, in order to provide waste rock drums with limestone treatments, and completely inert material with NPR, reacting with rain water alone.

PLATE 6: Average rock size in the experimental drums.

6. TAILINGS COLUMN EXPERIMENTS

The objective of the tailings columns experiments is to test the concept that placement of a cover on tailings, comprised of an NPR and "Eco-layer", will reduce or prevent acid generation. The key component of the " Eco-layer" is a heterotrophic bacterial population, supported by the root zone of a vegetation cover. The overall concept is presented in Schematic 6.

6.1 Tailings Column Experiment -1

In order to find an optimal configuration of such a cover, and to evaluate the overall effectiveness of such an approach, the following objectives will be addressed during the column experiment:

- Quantification of water distribution and flow properties in the zone between the surface and water table, in columns with different treatment design (configuration variables: type of NPR, layer thickness and type of "eco-layer).

- Quantification of oxygen consumption inside different types of "Eco-layers", and "Eco-layer" resistance to oxygen diffusion.

- Examination of bacterial population activities, and biofilm development on sulphide grain surfaces, caused by dissolution of NPR.

- Analysis of precipitate chemistry and microbial consortia comprising the biofilm.

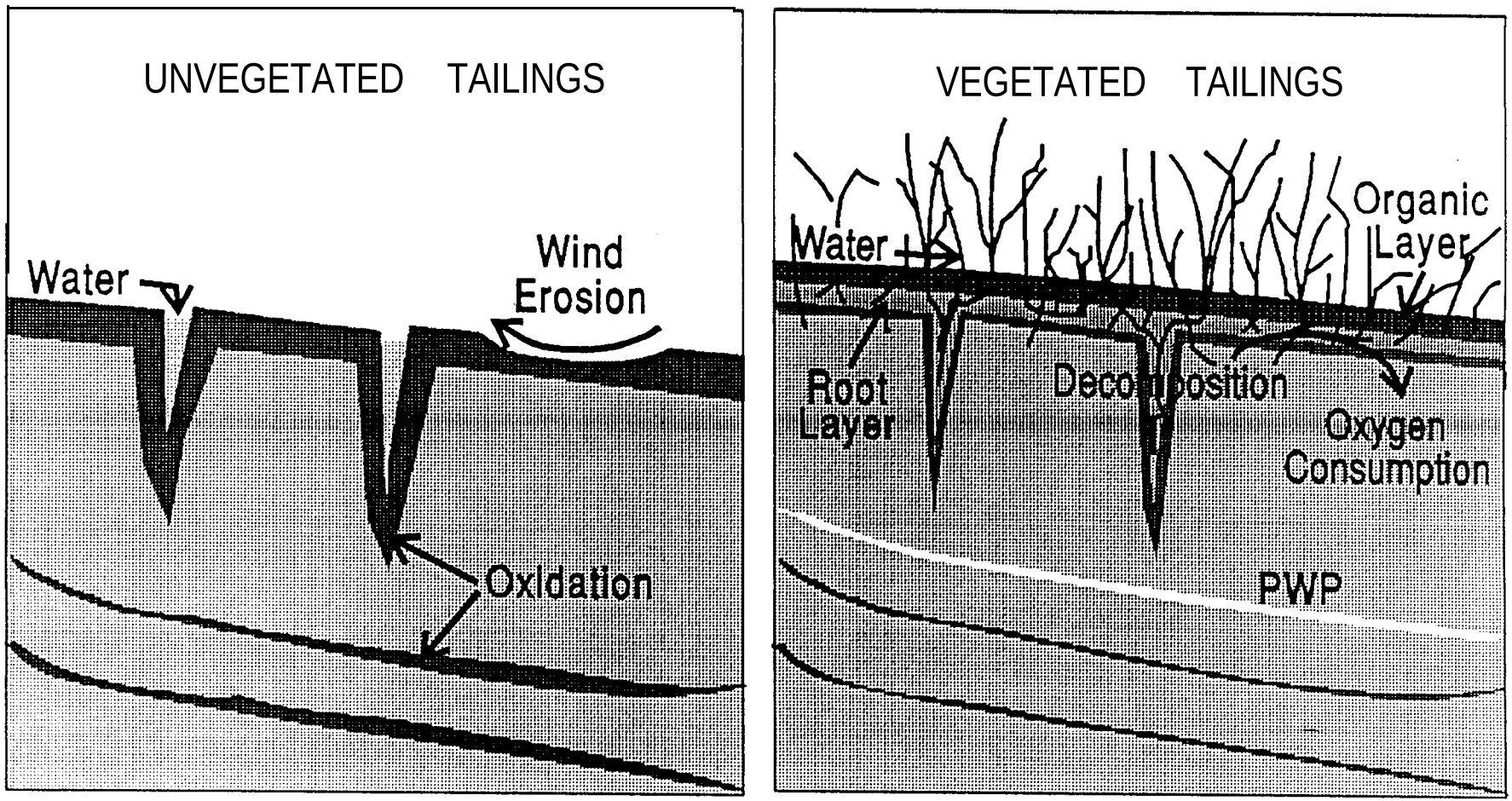
The oxidation of pyrite-rich tailings, which leads to AMD generation, is greatly accelerated by bacteria. The oxidation of pure pyrite by *Thiobacillus ferrooxidans* has been well characterized (Ehrlich 1990). These bacteria are able to utilise Fe^{2+} and or S^{-} as an energy source (electron donor). SEM studies have been carried out on the surface characteristics of pyrite (Walton 1988), and the effects of bacterial oxidation on surface morphology (Rodriguez-Leiva and Tributsch 1988; Pichtel and Dick 1991; Mustin et al. 1992). Corrosion pits on the crystal surfaces are associated with thiobacilli, which inhabit a biofilm (Rodriguez-Leiva and Tributsch 1988).

Biofilms provide diffusion barriers, which limit specific bacterial activities to zones only a few microns thick (Characklis and Marshall 1990). For example, corrosion of rock surfaces may be limited by the diffusion of oxygen through the biofilm. In nature, the heterogeneity of the surface chemistry and morphology and the intrinsic characteristics of biofilms indicate that a complex micro-environment will be established between the pyrite crystal matrix and the bacteria.

Examination of biofilms and precipitate deposits from both a microbiological and chemical point of view will provide insight into what may be limiting oxidation.

A sampling scheme and a methodology for the tailings columns experiment had to be developed to evaluate the effectiveness of the proposed cover; specifically the strategy must include testing whether the biofilm, which generates acid, is indeed inhibited by the heterotrophs, which are to be stimulated in the root zone of the vegetation layer. Details of the SEM work and the methodology are given in the Appendix.

For the microbiological studies, a vertical section of each tailings column will be cut out, sealed and replaced (such that it can be readily removed for sampling). The cylinders will be filled with fresh, saturated tailings, with or without an NPR layer. The surface will be roughened and a thin layer of woodchips placed on top (these treatments have been



EFFECT OF VEGETATION ON FRESH TAILINGS

Schematic 6

shown to assist in vegetation establishment in previous studies). Control columns without vegetation will also be set up, to test sampling procedures.

The columns will be destructively sampled to determine numbers and location of heterotrophs and pyrite-oxidising bacteria (*Thiobacillus*) in relation to depth in the column, roots, and cracks.

Columns will be laid on their side and the vertical window carefully removed. Plugs of tailings will be extracted at various locations with a wide-mouthed syringe.

Serial dilutions will be plated on Petrifilm (3M) or nutrient agar plates for heterotroph counts and into a liquid medium (McCready et al. 1986) for enumeration of thiobacilli by MPN.

Tailings Column Experiment -2

A second column experiment will be set up at the same time as the field experiments in the spring of 1993. Routine sampling of hydrology, drainage chemistry and microbiology will be carried out. Observations in the columns will be related to those made in the field.

The NPR layer, to be placed below the root zone, will serve several functions. One function is the neutralization of AMD which, due to capillary rise, will migrate in the vadose zone. Neutralization will occur through reactions between the ferric iron and the carbonate component of the NPR. The second function of the NPR layer is decrease the permeability of the tailings. This will occur following precipitate formation in the absence of bulk movement of water through the NPR layer, generating a 'hardpan' layer. The decrease in permeability of a layer within the vadose zone will result in higher moisture retention in the tailings cover and increased heterotrophic activity. Increased

heterotrophic activity will, in turn, lower oxygen concentrations and generate reducing conditions in the porewater.

Measurement of hydraulic conductivity with time, and analysis of chemical reactions between the NPR layer and tailings chemistry have to be completed. All measurements must be performed such that the parameters and results can be integrated into a program. A program and the computer code have been already been purchased, and the appropriate input parameters have been determined for the experiment, which can be integrated with existing computer codes. Oxygen diffusion programs for tailings covers have already been developed (Collin et al. 1990).

To adapt results to a comprehensive mathematical model of tailings aerated zone, it is necessary to:

- Assess changes in the NPR layer hydraulic conductivity as a function of time and environment chemistry;

- Verify "the best treatment" configuration and to scale up to pilot/field conditions;

Prior to set-up of the experimental columns, the data must be collected for the following determinations:

- Determine tailings moisture characteristics, using a soil moisture extractor.

- Determine tailing particle size characteristics, using an SA-22 Fritsch Analyzer.

- Determine NPR particle size characteristics, using an SA-22 Fritsch Analyzer.

- Determine sulphide content in tailings samples at a time of column set-up.

- Determine types and numbers of bacteria present in the tailings mass used in experiment (heterotrophs and *Thiobacillus*).

- Determine unsaturated vertical hydraulic conductivity in a control column, and its spatial distribution (static water level about 0.25 m above the bottom of a column) and recalculate in comparison to the field situation (collect information about grain distribution and dump methods in the field).

- Run column experiment and check tailing behaviour during short dry periods (crack development will destroy all hydraulic calculations).

- Consider winter simulation.

- Consider vertical seeps at the tailing-column interface area and try to find a solution.

6.3 Planned Measurements and Required Equipment

1. From the determination of the GRADIENT OF PRESSURE HEAD (tailing suction), the degree of saturation and hydraulic conductivity can be calculated. It is planned to insert about 8 measuring probes per column.

   The following equipment for measuring the GRADIENT OF PRESSURE HEAD were evaluated.

   - Set of soil moisture probes (tensiometer); $220.00 per set (vacuum dial gauge plus vent tube with ceramic tip); a system of measurement with one

or two gauges might be developed if it is possible to find a quick coupler between the gauge and vent tube (set of vent tube costs about $30.00); waiting time between connection and reading will occur due to achieving true equilibrium(minimum few hours to a maximum of 24 hours); tensiometer range 0-1 atm; manual reading.

- Thermocouple psychrometers; cost per unit, $15 @; microvoltometers about $500 @; switching unit about $300; chart recorder $400; reading range 1-80 atm. readings 0-1 atm with unpredictable error; best device for measuring suction in relatively dry, unsaturated soil; disadvantages: corrosion in acidic environment.

- Time domain reflectometry moisture measuring equipment; features depth integrated (0.15-0.70M) instantaneous volumetric water content; system can be programmed to autolog moisture readings; data could be dumped via RS-232 port to computer; cost about $15000.00; might be used for lab and field monitoring.

After consultation with various experts, it was decided that time domain reflectometry would be the most desirable measuring equipment. It can be transported to the field conditions, which is the ultimate test of the cover performance.

Given the costs involved in these measurements, an application has been made for funding from NRC. It was concluded that setting up the columns, without being in the position the measure the appropriate parameters for the cover development, would not be logical.

2. VOLUME of water percolating through the system. Location: outflow tubing. Possible equipment: to be determined

3. Location of WATER TABLE (possibly about 0.1 m above supporting plate) equal to water level inside the outflow tubing

4. EVAPORATION AND EVAPOTRANSPIRATION to be calculated in relation to temperature and humidity and climatic region in which the tailings cover is located.

5. TEMPERATURE inside the column

6. CONCENTRATION OF OXYGEN below the "Eco-layer". Possible equipment: to be determined.

Before commencing an experiment the following information must be obtained:

- tailings samples and NPR samples moisture characteristics for drying and wetting;

- tailings samples and NPR samples particle size characteristics, and bulk density;

- tailings samples and NPR samples capillary characteristics.

6.4 Column description

A number of identical columns using the following materials have been built:

- Cylinder body: Transparent extruded acrylic tubing, I.D. - 0.194 m, O.D. - 0.200 m, hight - 0.560 m;

- Supporting plate: Clear acrylic sheet - thickness 0.01 m;

- Plate-cylinder connection support circle - Clear acrylic sheet - thickness: 0.01m

- Connections - Solvent cement UN 1133 3.2 and silicone;

- Tubing - polyethylene tubing;

- Connection - polypropylene connectors and dura clamp flow valves.

Four columns have already been built and are being tested for leaks and strength under the tailings load.

Two columns have been set up with tailings to test sampling methods for hydrology and microbiology.

Experimental configuration of column setup will be determined after the decision has been reached on the NRC funding.

7. CONCLUSIONS AND RECOMMENDATIONS

Although full operation of the field test system was not achieved during the summer of l992, several conclusions can be drawn from the results obtained. The NPR pre-treatment is, overall, an effective means of removing iron and reducing acidity. The NPR material remained reactive over 47 days with one washing, despite problems with plugging, encountered due to decreases in permeability by accumulation of loose precipitates. At the time of freeze-up, 47% of the feed water acidity was removed, along with 76% of the dissolved iron. A total of 12.3% of the NPR was consumed during treatment of 160 L of AMD, equivalent to 3.1 g of NPR consumed per litre of AMD.

While NPR shows promise, an appropriate placement technique remains to be devised, such that one batch of NPR will remain in direct contact with, and serve to treat, AMD for a period of months. For instance, the requirement for only one NPR batch per summer, the period when the highest acidities occur in B-Ditch, is an appropriate target for full scale application of NPR.

During operation of the laboratory system, plugging was not encountered, as the precipitates were washed from the column once a week. Complete exhaustion of NPR had not occurred at the end of 52 days of operating the laboratory column experiment, which was terminated due to feed water depletion. It is recommended that a passive operating technique be developed, providing periodic agitation of NPR to effectively dislodge precipitates accumulating among NPR granules.

The precipitates resulting from NPR-AMD reactions have a lower wet volume than those produced with lime treatment. Although precipitates generated by the field and laboratory systems were analyzed, along with the treated water for the same time period, a complete mass balance of the elemental distribution in the water, precipitates and NPR could not be carried out. Only 18 to 25% of the iron reported to the precipitate mass. Pairs of sample weight and sample elemental analysis data were not available at the time of report writing.

It is recommended that a mass balance be completed before future field and laboratory system studies are carried out.

The biological components of the field test system were installed during the 1992 test period, but did not become operational before freeze-up. However, microbial activity was initiated in the field test system ARUM tank and algal populations have begun colonization in the Biological Polishing pools. Growth rates for algal populations in NPR-treated water have been determined from laboratory test work. Growth rates were measured, ranging from sustaining the populations to an 8.7% net increase per day. During 1993, all components of the field test system, including the biological populations, will likely become operational. It is recommended that testing of the proposed decommissioning scenario, using the field test system, should be continued in l993.

The waste rock experiment, testing spent and new NPR, has been designed and set up, while the 1992 objectives did not require that final results of the waste rock experiment be available. However, monitoring results of the weathered rock in the control drums (without NPR) indicate the onset of acid generation already. Experiments which are intended to simulate waste rock piles are exceedingly difficult to design. The 17 drum set-up constructed in an outdoor facility at Boojum, is operating well, and is producing the anticipated results. It is recommended that the scheduled monitoring of the experiment be continued.

If fresh tailings receive an application of NPR, which is in turn overlain with a vegetation layer, a low permeability stratum (iron precipitate hardpan) should develop beneath the vegetation layer, and provide suitable conditions for heterotrophic (oxygen-consuming) bacteria in the root zone. The tailings column experiments, designed in 1992, are based on this premise; if water penetration into tailings is reduced, and its oxygen content eliminated, generation of acid by tailings can be curtailed.

Successful techniques for establishing vegetation covers over fresh tailings were developed during field trials in 1990 and 1991. Vegetation plots have twice overwintered, and heterotrophic bacterial populations are present.

Determination of the optimal configuration and effectiveness of such a cover demands a high level of control over many parameters, practically achievable only in the laboratory. Given the costs associated with measurement of these and other parameters, an application has been made for funding from NRC. In the event of NRC funding, it is recommended that on-site measurements be continued, where required, for completion of these experiments.

8. REFERENCES

Blake, D.F. 1990. Scanning electron microscopy. In Instrumental surface analysis of geological material, ed. by Dale L. Perry. pp 11-43. VCH Publishers, New York

Campbell, R., and Porter, R. 1982. Low-temperature scanning microscopy of microorganisms in soil. Soil. Biol. Biochem. 14: 241-245

Collin, M., Lindberg, H., and Lindgren, M. 1990. Modelling of water and oxygen transport in layered soil covers, Kemakta Consultants, Sweden, AR 90-14.

Characklis, W.G., and Marshall, K.C. 1990. Biofilms Wiley Interscience, New York

Ehrlich, H.L. 1990. Geomicrobiology, 2nd edition.

Fyson, A., Kerr, P., Lott, J.N.A., and Oaks, A. 1988. The structure of the rhizosphere of maize seedling roots-a cryogenic electron microscopy study. Can. J. Bot., 66: 2431-2435

McCready, R.G.L., Wadden, D., and Marchbank, A. 1986. Nutrient requirements for the in-place leaching of uranium by *Thiobacillus ferrooxidans*. Hydrometallurgy 17: 61-71

Mustin, C., Berthelin, J., Marion, P., and Donato, P. de 1992. Corrosion and electrochemical oxidation of a pyrite by *Thiobacillus ferrooxidans*. Appl. Environ. Microbiol. 58: 1175-1182

Pichtel, J.R., and Dick, W.A. 1991. Sulfur, iron and solid phase transformations during the biological oxidation of pyritic mine spoil. Soil Biol. Biochem. 23: 101-107

Read, N.D., Porter, R., and Beckett, A. 1983. Comparison of Preparative techniques for the examination of the external morphology of fungal material with the scanning electron microscope. Can. J. Bot. 61: 2059-2078

Rodriguez-Leiva, M., and Tributsch, H. 1988. Morphology of bacterial leaching patterns by *Thiobacillus ferrooxidans* on synthetic pyrite . Arch. Microbiol. 149: 401-405

Scott, D. 1991. Gibraltar's dump leaching-an insight into acid effluent control. The Northern Miner, September

Southam, G., and Beveridge, T.J. 1992. Enumeration of thiobacilli within pH-neutral and acidic mine tailings and their role in the development of secondary mineral soil. Appl. Environ. Microbiol. 58: 1904-1912

Walton, J.E. 1988. SEM petrology atlas. The American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A.

9. APPENDIX

LIST OF TABLES AND FIGURES AND NOTES

Table A1: Chemical Characteristics of Selbaie Field System

SAMPLE DATE	11-08-92	17-08-92	17-08-92	17-08-92	11-08-92	17-08-92	11-08-92	17-08-92	11-08-92	17-08-92
SAMPLE VOLUME	100	100	100	100	100	100	100	100	100	100
ASSAYERS CODE	4046	4055	4057	4058	4047	4056	4048	4059	4053	4064
SAMPLING LOCATION	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE
	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys
	Feed	Feed	PR1-PR2	Settling	BP1#1	BP1#1	BP1#5	BP1#5	BP2	BP2
	surface	surface	PR3	Tank	surface	surface	surface	surface	surface	surface
Processing code	FA	FA	FA	FA	FA	FA	FA	FA	FA	FA
** F I E L D **										
Temp. (C)	11.2	23.7	24.6	24.7	11.2	23	11.2	22.7	12.3	21.8
pH	2.13	2.41	4.54	4.5	2.46	2.98	2.49	2.87	2.78	3.09
Cond. (umhos/cm	9002	8760	6880	6850	7500	7950	7750	7530	7320	7590
Eh (mV)	462	691	441	433	408	644	408	650	278	520
** L A B **										
Temp. (C)	9	14	17	16	9	15	9	15	9	17
pH	2.64	2.57	4.37	4.42	3.02	2.88	2.95	2.84	3.25	3.12
Cond. (umhos/cm	5500	5500	5000	5000	5000	5000	5000	5000	4750	5600
Eh (mV)	428	456	228	205	370	412	373	433	223	261
Acidity (mg/l)	7725	18700	3475	3550	5825	2950	5050	4100	4325	4100
ELEMENTS Ag	0.572	0.575	0.145	0.003	0.202	0.165	0.205	0.167	0.08	0.106
Al	233	235	24.4	22.7	98.8	60.5	99.4	71.7	50.4	59.9
Ba	0.036	0.035	0.048	0.045	0.088	0.06	0.086	0.065	0.069	0.071
Ca	386	398	567	604	604	601	644	651	617	595
Cd	3.6	3.66	3.09	2.93	3.04	3.03	3.12	3.05	2.55	2.75
Co	0.774	1.04	0.739	0.7	0.744	0.866	0.721	0.882	0.551	0.591
Cr	0.073	0.073	0.011	0.011	0.029	0.021	0.033	0.019	0.056	0.06
Cu	370	349	130	119	184	151	184	158	53.1	78.5
Fe	1660	1580	103	103	400	157	400	183	883	771
K	3.1	2.8	7.1	7.7	31	22	29.8	24.5	81.3	70.6
Mg	449	463	501	469	426	482	427	479	346	369
Mn	65.6	53.9	50.9	48.1	50.7	51.2	51.8	50.5	41	44
Na	8.26	8.6	31.9	29.3	30.2	33.7	29.9	33.4	24.8	26.7
Ni	0.33	0.36	0.43	0.41	0.39	0.44	0.4	0.43	0.36	0.39
S	2790	2900	1580	1580	1890	1800	1970	1840	1840	1870
Si	35.7	37.3	17.5	16.6	27.5	23.3	28.9	24.9	25.2	26.4
Sn	0.47	0.51	0.68	0.66	0.6	0.69	0.67	0.68	0.27	0.33
Sr	0.43	0.439	6.87	6.42	4.14	5.82	4.09	5.38	2.92	3.25
U	<0.02	not done	not done	not done	<0.02	not done	not done	not done	not done	not done
Zn	943	927	483	469	483	483	493	480	698	723
Phosphate	7.6	not done	not done	not done	4.5	not done	3.7	not done	2.9	not done

Table A2: Flow Path of Feed Water to the Field System

Date of Oper'n	Tank Level, L (appx.)	Feed Tank Batch	Flow L/day	Batch out of PR1-3	No. of Time Volume Turned Ove	Batch out of S-T	No. of Time Volume Turned Ove	Batch out of BP1	No. of Time Volume Turned Ove	Batch out of BP2	No. of Time Volume Turned Ove
05-Jul		05-Jul						05-Jul	1900		
06-Jul		I									
07-Jul		05-Jul						05-Jul	1900		
08-Jul		08-Jul		08-Jul	filled	08-Jul	filed	08-Jul			
17-Jul		08-Jul	216	08-Jul	0.4	08-Jul	1.1	08-Jul	0.1		
18-Jul		08-Jul	216	I	0.8	I	2.2	I	0.2		
19-Jul	5404	19-Jul	216	I	1.3	I	3.2	I	0.3		
20-Jul	5188	I	216	08-Jul	1.7	I	4.3	I	0.5		
21-Jul	4972	I	216	19-Jul	2.1	08-Jul	5.4	I	0.6		
22-Jul	4756	I	216	I	2.5	19-Jul	6.5	I	0.7		
23-Jul	4540	I	216	I	2.9	I	7.6	I	0.8		
24-Jul	4324	I	216	I	3.4	I	8.6	I	0.9		
25-Jul	4108	I	216	I	3.8	I	9.7	I	1.0		
26-Jul	3892	I	216	I	4.2	I	10.8	I	1.1		
27-Jul	3676	I	216	I	4.6	I	11.9	I	1.3		
28-Jul	3460	I	216	I	5.0	I	13.0	I	1.4		
29-Jul	3244	I	216	I	5.5	I	14.0	08-Jul	1.5		
30-Jul	3028	19-Jul	216	19-Jul	5.9	19-Jul	15.1	19-Jul	1.6	19-Jul	half full
11-Aug	4500	11-Aug	250	empty	0.0	empty	0.0	19-Jul	filling	19-Jul	filling
12-Aug	4250	I	250	filling	0.0	empty	0.0	I	filling	I	filling
13-Aug	4000	I	250	11-Aug	0.5	filling	0.0	I	filling	I	filling
14-Aug	3800	I	200	I	0.9	11-Aug	1.0	I	1.7	I	filling
15-Aug	3500	I	300	I	1.5	I	2.5	I	1.9	I	0.2
16-Aug	3200	I	300	I	2.0	I	4.0	I	2.0	I	0.3
17-Aug	3000	I	200	I	2.4	I	5.0	I	2.1	I	0.4
18-Aug	2750	I	250	I	2.9	I	6.3	I	2.2	I	0.6
19-Aug	2500	I	250	I	3.4	I	7.5	I	2.4	I	0.7
20-Aug	2300	11-Aug	200	I	3.8	I	8.5	I	2.5	I	0.8
21-Aug	4700	21-Aug	216	I	4.2	I	9.6	19-Jul	2.6	I	0.9
22-Aug	4500	I	200	11-Aug	4.6	I	10.6	11-Aug	2.7	I	1.0
23-Aug	4250	I	250	21-Aug	5.1	11-Aug	11.8	I	2.8	I	1.1
24-Aug	4000	I	250	I	5.6	21-Aug	13.1	I	3.0	I	1.3
25-Aug	3800	I	200	I	6.0	I	14.1	I	3.1	I	1.4
26-Aug	3600	I	200	I	6.3	I	15.1	I	3.2	I	1.5
27-Aug	3350	I	250	I	6.8	I	16.3	I	3.3	I	1.6
28-Aug	3150	I	200	I	7.2	I	17.3	I	3.4	I	1.7
29-Aug	2800	I	350	I	7.9	I	19.1	I	3.6	19-Jul	1.9
30-Aug	2700	21-Aug	100	21-Aug	8.1	21-Aug	19.6	11-Aug	3.7	11-Aug	2.0
16-Sep	5500	16-Sep	200	21-Aug	8.5	21-Aug	20.6	11-Aug	3.8	11-Aug	2.1
17-Sep	5300	I	200	21-Aug	8.9	I	21.6	21-Aug	3.9	I	2.2
18-Sep	5000	I	300	16-Sep	9.4	21-Aug	23.1	I	4.0	I	2.3
19-Sep	4800	I	200	I	9.8	16-Sep	24.1	I	4.1	I	2.4
20-Sep	4600	I	200	I	10.2	I	25.1	I	4.2	I	2.5
21-Sep	4384	I	216	I	10.6	I	26.2	I	4.3	I	2.6
22-Sep	4250	I	134	I	10.9	I	26.8	I	4.4	I	2.7
23-Sep	4000	I	250	I	11.4	I	28.1	I	4.5	I	2.9
24-Sep	3750	I	250	I	11.9	I	29.3	I	4.7	11-Aug	3.0
25-Sep	3475	I	275	I	12.4	I	30.7	I	4.8	21-Aug	3.1
26-Sep	3200	I	275	I	12.9	I	32.1	21-Aug	5.0	I	3.3
27-Sep	2925	I	275	I	13.5	I	33.5	16-Sep	5.1	I	3.4
28-Sep	2650	I	275	I	14.0	I	34.8	I	5.3	I	3.6
29-Sep	2434	I	216	I	14.4	I	35.9	I	5.4	I	3.7
30-Sep	2218	I	216	I	14.9	I	37.0	I	5.5	I	3.8
01-Oct	2002	I	216	I	15.3	I	38.1	I	5.6	I	3.9
02-Oct	2002	I	0	I	15.3	I	38.1	I	5.6	I	3.9
03-Oct	2002	16-Sep	0	16-Sep	15.3	16-Sep	38.1	16-Sep	5.6	21-Aug	3.9

Table A3: Precipitate Analysis of PR Field System

SAMPLE DATE	25-08-92	25-08-92	25-08-92	25-08-92	25-08-92	25-08-92
ASSAYERS CODE	4067	4068	4069	4070	4071	4072
SAMPLING	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE
LOCATION	PR	PR	PR	PR	PR	PR
	top	top	middle	middle	bottom	bottom
Processing code	SS	SS	SS	SS	SS	SS
ELEMENTS Ag	7	19	13	10	8	12
ug/g Al	4980	27000	21600	12500	9340	56400
As	<10	<10	<10	<10	<10	<10
B	<2	<2	2	<2	<2	<2
Ba	19	3	3	3	4	4
Be	<1	<1	<1	<1	<1	<1
Bi	<8	<8	<8	<8	<8	<8
Ca	129000	103000	105000	110000	87200	61200
Cd	<1	<1	<1	<1	<1	<1
Co	<1	<1	<1	<1	<1	3
Cr	36	27	23	22	23	12
Cu	2760	14	8460	5560	4480	13000
Fe	184000	204000	200000	188000	187000	75700
K	1380	488	692	408	474	<80
Mg	840	780	306	352	90	223
Mn	36	103	66	63	39	47
Mo	<2	<2	<2	<2	<2	<2
Na	436	296	68	52	12	<3
Ni	5	8	4	7	4	7
P	22600	5740	7500	6920	7460	4090
Pb	15	<3	<3	<3	<3	9
S	38000	20200	34700	33400	33600	60900
Se	<10	<10	<10	<10	<10	<10
Si	182	239	168	188	80	426
Sn	<8	<8	<8	<8	<8	10
Sr	652	442	434	456	424	288
Ti	4	<2	<2	<2	<2	5
U	<5	not done	not done	not done	not done	<5
V	14	6	6	6	4	3
Zn	2020	7300	4320	3680	2660	6010

Table A4: Chemical Characteristics of the ARUM Tank

SAMPLE DATE	11-08-92	17-08-92	11-08-92	17-08-92	11-08-92	17-08-92	11-08-92	17-08-92
SAMPLE VOLUME	100	100	100	100	100	100	100	100
ASSAYERS CODE	4049	4060	4050	4061	4051	4062	4052	4063
SAMPLING LOCATION	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE	SELBAIE
	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys	Test Sys
	ARUM	ARUM	ARUM pipe	ARUM pipe	ARUM pipe	ARUM pipe	ARUM pipe	ARUM pipe
	surface	surface	top	top	middle	middle	bottom	bottom
Processing code	FA	FA	FA	FA	FA	FA	FA	FA
** F I E L D **								
Temp. (C)	12.5	19.5	12.7	15.6	12.7	15.8	12.2	16.1
pH	3.41	3.96	3.42	4	3.44	3.83	3.98	3.84
Cond. (umhos/cm	6170	6160	6210	6750	7330	7070	7120	7170
Eh (mV)	262	469	274	417	262	412	177	410
** L A B **								
Temp. (C)	9	16	9	16	9	16	9	16
pH	4.01	4	3.81	4.19	3.9	3.91	4.23	3.94
Cond. (umhos/cm	4000	4800	4400	5000	4550	5000	4500	5000
Eh (mV)	185	226	170	151	172	148	163	130
Acidity (mg/l)	3175	3100	4825	4950	5450	5150	4950	4850
ELEMENTS Ag	0.091	0.076	0.075	0.061	0.071	0.061	0.069	0.049
Al	35.4	30.2	59.7	37.7	55.8	45.9	43.3	41.4
Ba	0.054	0.046	0.06	0.053	0.065	0.053	0.061	0.048
Ca	585	541	556	529	548	501	569	494
Cd	2.91	2.89	3.19	2.56	2.9	2.66	2.61	2.64
Co	0.626	0.684	0.553	0.567	0.541	0.54	0.495	0.523
Cr	0.021	0.019	0.056	0.047	0.048	0.049	0.051	0.053
Cu	77.5	62.3	49.3	29.9	46.5	35.1	37.2	25.9
Fe	309	349	1010	1190	1050	1110	1130	952
K	24.5	25.5	88.7	139	138	122	144	85.3
Mg	370	385	311	280	293	267	287	288
Mn	43.8	42.9	39.7	34.2	37.8	33.7	34.9	36.2
Na	23.4	22.9	20.4	19.4	20	18.5	19.7	19.5
Ni	0.33	0.34	0.36	0.33	0.32	0.32	0.36	0.36
S	1530	1440	1740	1680	1850	1640	1800	1610
Si	19	18.4	16.7	24.2	27.3	24	25.5	23.6
Sn	0.52	0.48	0.32	0.23	0.29	0.26	0.24	0.25
Sr	4.69	4.36	1.92	1.2	1.25	1.13	1.23	1.81
U	not done	not done	<0.02	not done	not done	not done	not done	not done
Zn	450	444	429	595	699	590	599	601
Phosphate	3.3	not done	3.7	not done	3.7	not done	4.1	not done

Table A5: ICP Analysis of Growth Experiment 4 Algae

ELEMENT	B2-PO4 TREATED W/O NITROGEN	B2-PO4 TREATED W/ NITROGEN
	ug/g	ug/g
Al	17604	14849
B	11684	12841
Ba	15840	15753
Ca	118016	138180
Cu	529	311
Fe	11233	4159
P	2215	1765
S	109390	120998
Ti	1359	742
Zn	14232	14107

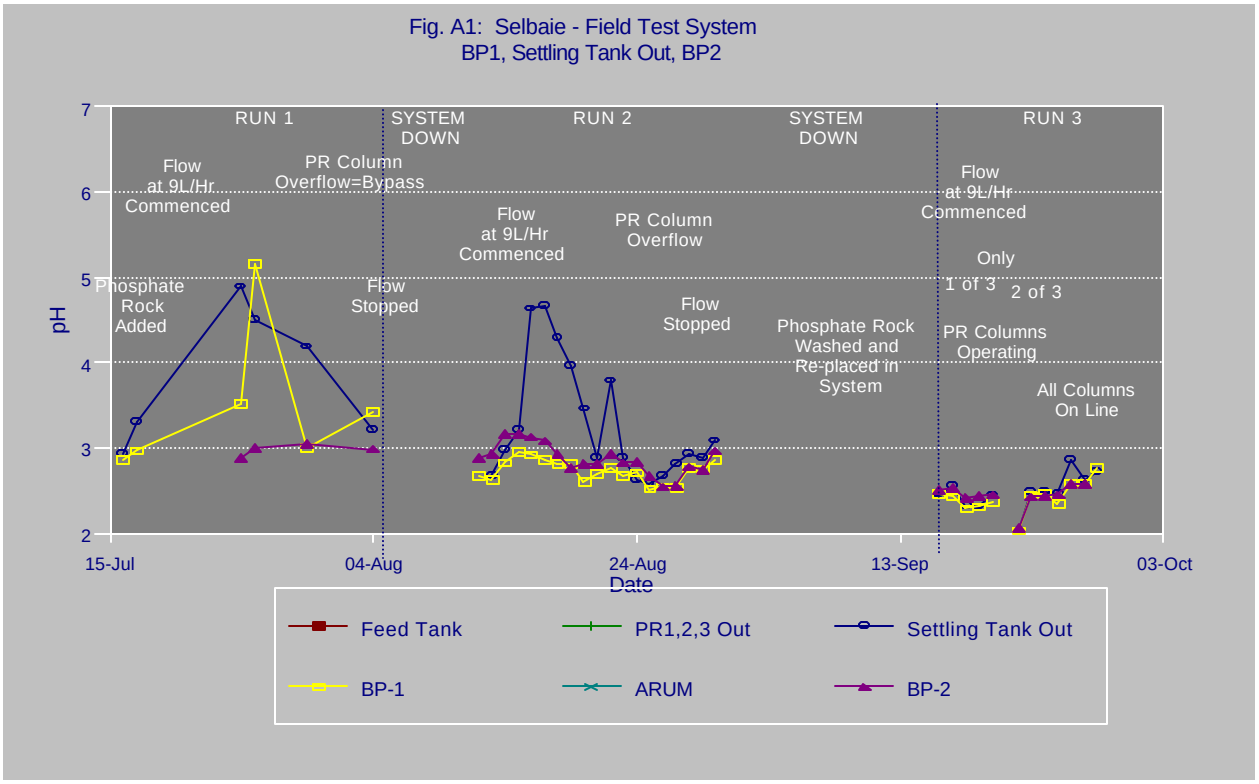


Fig. A1: Selbaie - Field Test System
BP1, Settling Tank Out, BP2
RUN 1
SYSTEM DOWN
RUN 2
SYSTEM DOWN
RUN 3
Flow at 9L/Hr Commenced
PR Column Overflow=Bypass
Phosphate Rock Added
Flow Stopped
Flow at 9L/Hr Commenced
PR Column Overflow
Flow Stopped
Phosphate Rock Washed and Re-placed in System
Flow at 9L/Hr Commenced
Only 1 of 3
2 of 3
PR Columns Operating
All Columns On Line
pH
Date
15-Jul
04-Aug
24-Aug
13-Sep
03-Oct
Feed Tank
PR1,2,3 Out
Settling Tank Out
BP-1
ARUM
BP-2

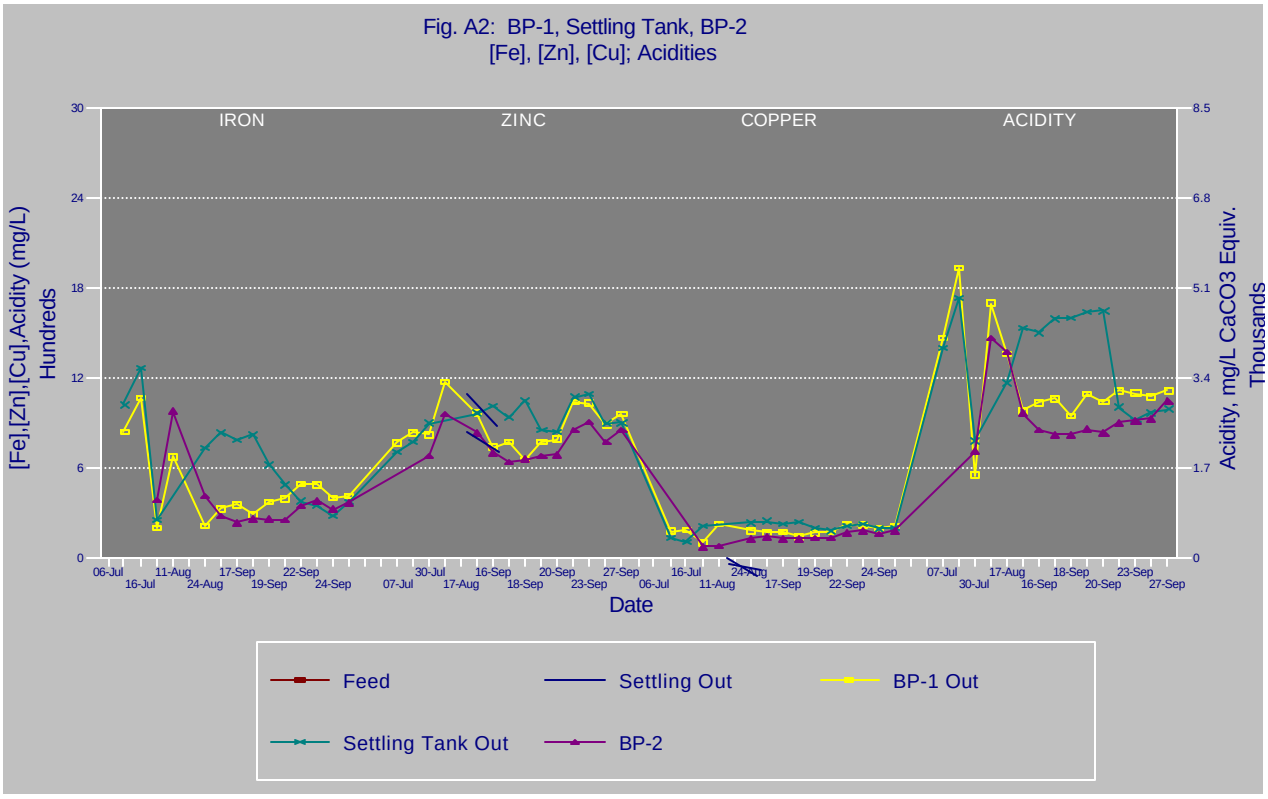


Fig. A2: BP-1, Settling Tank, BP-2
[Fe], [Zn], [Cu]; Acidities
IRON
ZINC
COPPER
ACIDITY
[Fe],[Zn],[Cu],Acidity (mg/L)
Hundreds
Acidity, mg/L CaCO3 Equiv.
Thousands
Date
Feed
Settling Out
BP-1 Out
Settling Tank Out
BP-2

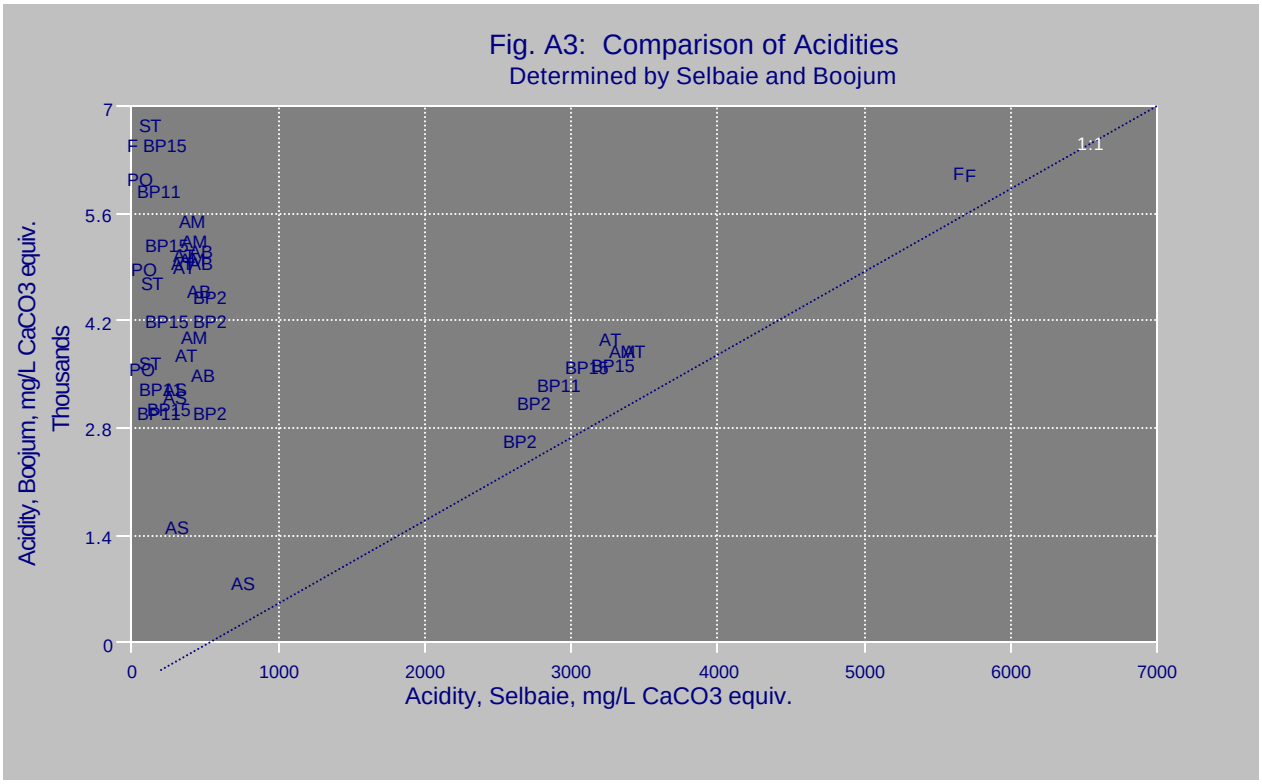


Fig. A3: Comparison of Acidities
Determined by Selbaie and Boojum
Acidity, Boojum, mg/L CaCO3 equiv.
Thousands
Acidity, Selbaie, mg/L CaCO3 equiv.
1:1
0
1000
2000
3000
4000
5000
6000
7000
1.4
2.8
4.2
5.6

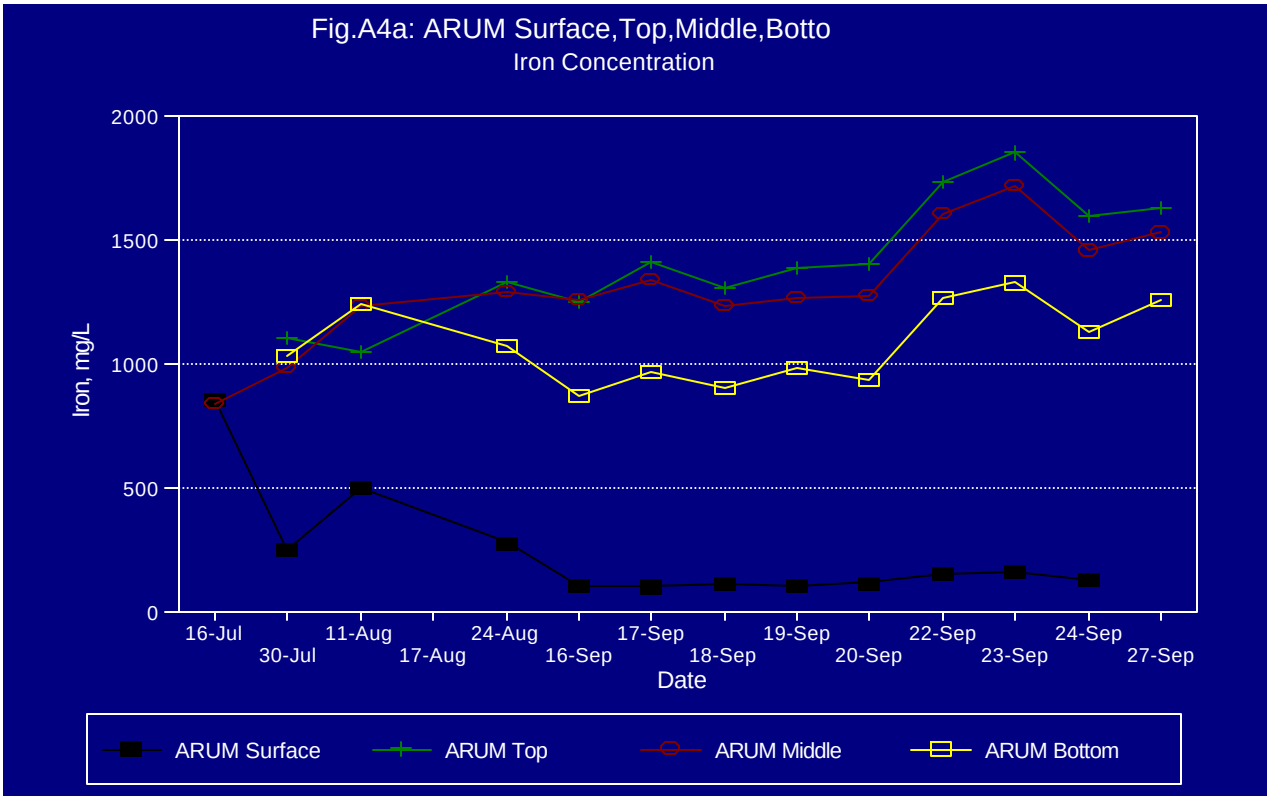


Fig.A4a: ARUM Surface,Top,Middle,Botto
Iron Concentration
Iron, mg/L
2000
1500
1000
500
0
16-Jul
30-Jul
11-Aug
17-Aug
24-Aug
16-Sep
17-Sep
18-Sep
19-Sep
20-Sep
22-Sep
23-Sep
24-Sep
27-Sep
Date
ARUM Surface
ARUM Top
ARUM Middle
ARUM Bottom

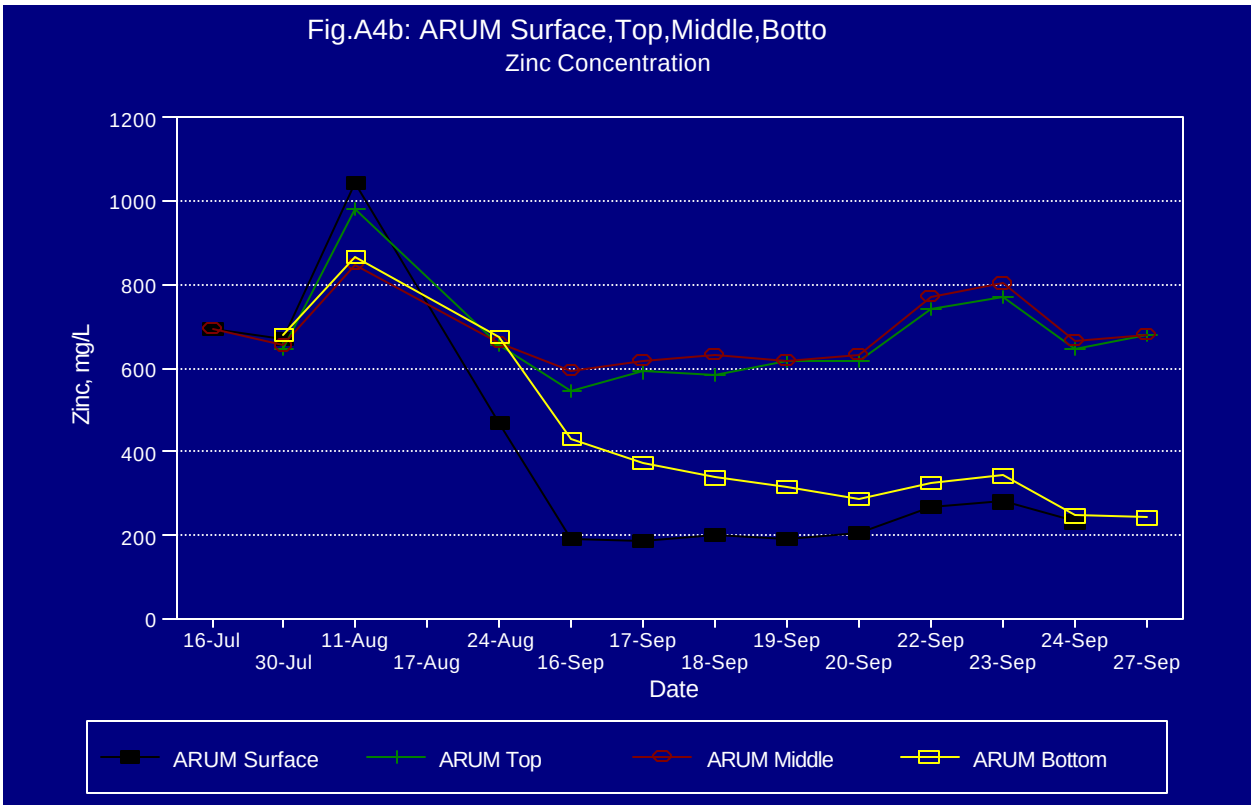


Fig.A4b: ARUM Surface,Top,Middle,Botto
Zinc Concentration
Zinc, mg/L
1200
1000
800
600
400
200
0
16-Jul
30-Jul
11-Aug
17-Aug
24-Aug
16-Sep
17-Sep
18-Sep
19-Sep
20-Sep
22-Sep
23-Sep
24-Sep
27-Sep
Date
ARUM Surface
ARUM Top
ARUM Middle
ARUM Bottom

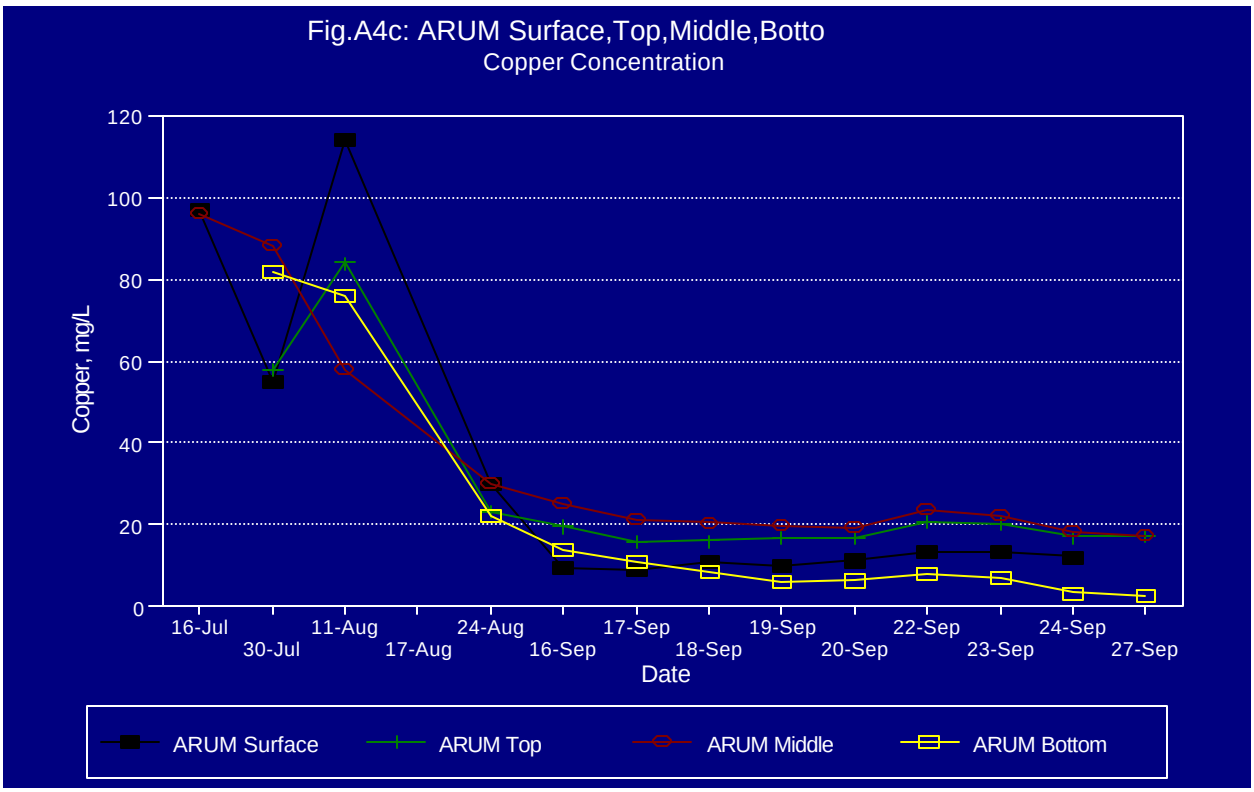


Fig.A4c: ARUM Surface,Top,Middle,Botto
Copper Concentration
Copper, mg/L
120
100
80
60
40
20
0
16-Jul
30-Jul
11-Aug
17-Aug
24-Aug
16-Sep
17-Sep
18-Sep
19-Sep
20-Sep
22-Sep
23-Sep
24-Sep
27-Sep
Date
ARUM Surface
ARUM Top
ARUM Middle
ARUM Bottom

APPENDIX 1 - SEM INVESTIGATION OF BIOFILMS ON PYRITE

Conventional SEM would employ critical point drying prior to examination. The McMaster facility is equipped for cryo SEM. Instead of drying, the sample is very rapidly frozen in semi-solid nitrogen (-220 C). This procedure preserves the hydrated materials without the distortions caused by drying (Campbell and Porter 1982; Read et al 1983; Fyson et al 1988). In other words, the three-dimensional relationships between rock-surface, biofilms and precipitates are preserved.

The water may obscure the location of bacteria. This can be overcome, either by fracturing the biofilm on the microscope stage and by etching (localised heating) of the sample to progressively sublime the water and reveal previously buried material.

Preservation of the hydrated state will also preserve the chemistry of the surface materials (Blake 1990). Comparison to reference solutions in conjunction with EDX analysis will help identify the compounds in the aqueous layer, i.e. suspended solids and solutes. EDX analysis can also help identify precipitates and in conjunction with direct observation of crystal characteristics, the chemistry of surface materials.

Thiobacilli will be isolated and enumerated. Also other bacteria present will be characterised.

SEM STUDIES

SEM studies will be carried out at McMaster on the [MODEL] microscope fitted with a cryo stage and linked to [MODEL] electron dispersive X ray analyzer. For SEM studies of rock surfaces, samples need to be smaller than the dimensions of the stubs (1 cm circle x 1 cm high) for insertion into the microscope. It is essential to sample the rock material with as little perturbation of the surface as possible and with rapid preparation prior to microscopic examination. Cutting samples after incubation but prior to SEM will inevitably be disturbed with deposition of rock dust and disruption and displacement of biofilms. To avoid these problems, rock samples will be crushed and pieces approximately 5 mm in diameter will be placed in the drums. Samples of each rock type will be cut to provide a smooth surface for SEM and bacterial sampling and then crushed to provide sub-samples for SEM. Sub samples will be selected with a cut face an internal face (unweathered) and an external face (weathered).

All three faces will be examined by SEM. To ensure that these subsamples are exposed to the same environment as the other rocks in the column, the following procedure will be followed. One rock sample will be removed from the column. The 5 mm samples will be mounted onto the mother rock and this then placed back in the column in its original position. The sub-samples will be mounted on small pieces of plexiglass (less than 1 cm in diameter) with an inert adhesive (epoxy-resin) which in turn will be attached to the mother rock by inert

epoxy resin. At time of sampling for SEM, the mother rock will be recovered and transferred to an insulated box with 100 % humidity (to maintain incubation conditions) and transported to McMaster (approximately one hour).

The plexiglass holding the sub sample will be held with forceps and snapped off the mother rock. The sub samples will be then be processed (mounted on stub and coated) for examination by SEM. On each sampling date, one mother rock with a minimum of ten attached subsamples will be required from each waste rock drum. For each rock type, samples will be examined with or without the presence of NPR, a total of 15 combinations. Two samples will be examined for each treatment. Samples will be collected on three occasions;

-spring 1993 after winter exposure
-autumn 1993 after summer weathering
-spring 1994 after second winter weathering

A total of 75 samples is anticipated.

Samples for SEM will be mounted on stubs (one per stub) and examined without coating (where etching required), with carbon coating (where EDX required) or with gold-palladium coating (where surface morphology is to be examined in detail). Uncoated specimens will be examined first and subsequently coated after etching. Samples will be photographed using a Polaroid camera. This enables images to be examined immediately and help make decisions on how to proceed further. EDX analysis will be carried out on selected fields to characterise the chemistry of morphological features.

Dry stored Gibraltar rocks with coatings known to inhibit oxidation will be examined by SEM with EDX to determine the chemical nature of the surface covering materials. This will be compared the coatings Gibraltar rocks - developed in the experiments.
i) Rocks with coatings will be examined by SEM with X-ray analysis to determine the extent and location of coatings.

MICROBIOLOGY

Isolation and enumeration of bacteria. Bacteria will be washed off the surfaces of cut rocks from the columns. Thiobacilli will be enumerated by most probable number methods (MPN) in standard media (McCready et al 1986). Other bacteria will be isolated from NPR columns and characterized.

MODELLING AND MONITORING OF THE SECOND COLUMN EXPERIMENT

A second column experiment will be set up at the same time as the field experiments in the spring of 1993. Routine sampling of hydrology, drainage chemistry and microbiology will be carried out. Observations in the columns will be related to those made in the field.
The NPR layer, to be placed below the root zone, will serve several functions. One function is the neutralization of AMD which, due to capillary rise, will migrate in the vadose zone. Neutralization will occur through reactions between the ferric iron and the carbonate component of the NPR. The second function of the NPR layer is decrease the permeability of the tailings. This will occur following precipitate formation in the absence of bulk movement of water through the NPR layer, generating a `hardpan' layer. The decrease in permeability of a layer within the vadose zone will result in higher moisture retention in the tailings cover and increased heterotrophic activity. Increased heterotrophic activity will, in turn, lower oxygen concentrations and generate reducing conditions in the porewater.

Measurement of hydraulic conductivity with time, and analysis of chemical reactions between the NPR layer and tailings chemistry have to be completed. All measurements must be performed such that the parameters and results can be integrated into a program. A program and the computer code have been already been purchased, and the appropriate input parameters have been determined for the experiment, which can be integrated with existing computer codes. Oxygen diffusion programs for tailings covers have already been developed (Collin et al. 1990).

To adapt results to a comprehensive mathematical model of tailings aerated zone, it is necessary to:

- Assess changes in the NPR layer hydraulic conductivity as a function of time and environment chemistry;
- Verify "the best treatment" configuration and to scale up to pilot/field conditions;

Prior to set-up of the experimental columns, the data must be collected for the following determinations:

- Determine tailings moisture characteristics, using a soil moisture extractor.
- Determine tailing particle size characteristics, using an SA-22 Fritsch Analyzer.

- Determine NPR particle size characteristics, using an SA-22 Fritsch Analyzer.
- Determine sulphide content in tailings samples at a time of column set-up.
- Determine types and numbers of bacteria present in the tailings mass used in experiment (heterotrophs and *Thiobacillus*).
- Determine unsaturated vertical hydraulic conductivity in a control column, and its spatial distribution (static water level about 0.25 m above the bottom of a column) and recalculate in comparison to the field situation (collect information about grain distribution and dump methods in the field).
- Run column experiment and check tailing behaviour during short dry periods (crack development will destroy all hydraulic calculations).
- Consider winter simulation.
- Consider vertical seeps at the tailing-column interface area and try to find a solution.

Planned Measurements and Required Equipment

1. From the determination of the GRADIENT OF PRESSURE HEAD (tailing suction), the degree of saturation and hydraulic conductivity can be calculated. It is planned to insert about 8 measuring probes per column.

   The following equipment for measuring the GRADIENT OF PRESSURE HEAD were evaluated.

   - Set of soil moisture probes (tensiometer); $220.00 per set (vacuum dial gauge plus vent tube with ceramic tip); a system of measurement with one or two gauges might be developed if it is possible to find a quick coupler between the gauge and vent tube (set of vent tube costs about $30.00); waiting time between connection and reading will occur due to achieving true equilibrium(minimum few hours to a maximum of 24 hours); tensiometer range 0-1 atm; manual reading.
   - Thermocouple psychrometers; cost per unit, $15 @; microvoltometers about $500 @; switching unit about $300; chart recorder $400; reading range 1-80 atm. readings 0-1 atm with unpredictable error; best device for measuring suction in relatively dry, unsaturated soil; disadvantages: corrosion in acidic environment.

- Time domain reflectometry moisture measuring equipment; features depth integrated (0.15-0.70M) instantaneous volumetric water content; system can be programmed to autolog moisture readings; data could be dumped via RS-232 port to computer; cost about $15000.00; might be used for lab and field monitoring.

After consultation with various experts, it was decided that time domain reflectometry would be the most desirable measuring equipment. It can be transported to the field conditions, which is the ultimate test of the cover performance.

Given the costs involved in these measurements, an application has been made for funding from NRC. It was concluded that setting up the columns, without being in the position the measure the appropriate parameters for the cover development, would not be logical.

2. VOLUME of water percolating through the system. Location: outflow tubing. Possible equipment: to be determined

3. Location of WATER TABLE (possibly about 0.1 m above supporting plate) equal to water level inside the outflow tubing

4. EVAPORATION AND EVAPOTRANSPIRATION to be calculated in relation to temperature and humidity and climatic region in which the tailings cover is located.

5. TEMPERATURE inside the column

6. CONCENTRATION OF OXYGEN below the "Eco-layer". Possible equipment: to be determined.

Before commencing an experiment the following information must be obtained:

- tailings samples and NPR samples moisture characteristics for drying and wetting;

- tailings samples and NPR samples particle size characteristics, and bulk density;

- tailings samples and NPR samples capillary characteristics.

Column description

A number of identical columns using the following materials have been built:

- Cylinder body: Transparent extruded acrylic tubing, I.D. - 0.194 m, O.D. - 0.200 m, hight - 0.560 m;
- Supporting plate: Clear acrylic sheet - thickness 0.01 m;
- Plate-cylinder connection support circle - Clear acrylic sheet - thickness: 0.01m
- Connections - Solvent cement UN 1133 3.2 and silicone;
- Tubing - polyethylene tubing;
- Connection - polypropylene connectors and dura clamp flow valves.

Four columns have already been built and are being tested for leaks and strength under the tailings load.

Two columns have been set up with tailings to test sampling methods for hydrology and microbiology.

Experimental configuration of column set-up will be determined after the decision has been reached on the NRC funding.